A Constraint Based Model of the Design Process:
Complexity, Uncertainty, and Change

DISSERTATION

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By

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Abstract

Products, users, cultures, and designers all interact in complex, non-linear ways, as designers, users, and organizations each attempt to meet their own unique goals. The design and performance of today's products are influenced by technological change, mechanical design, design for manufacture, human factors, psychology, anthropology, legal concerns, regulations, and market pressures. As a result, product design is inherently multidisciplinary, and there is a need to balance a complex set of factors that characterizes the product's performance. Additionally, in a truly complex environment, designs are not static. Trade-offs, uncertainty, and change typify most physical products, as designs shift and grow alongside users, patterns of use, and contexts. In ways strongly reminiscent of coevolution, artifacts shape stakeholders' understandings, tasks, and goals, just as those things shape future designs. This is central to what makes design challenging to do, and to study.

This work serves as an introduction to complex systems, and explains in detail the principles, patterns, and phenomenon that underlie the design and performance of physical artifacts. It attempts to help designers of all types to navigate complexity within the design process, and to manage its effects on artifacts themselves. This was accomplished in three primary ways: an overview of existing complexity literature, the introduction of a constraint framework, and the development of a constraint management tool.

This work present a solid theoretical background grounded in engineering design theory, as well as elements of complex adaptive systems, design constraints, product architecture, and design evolution. It situates products and contemporary product design in the larger field of complex adaptive systems, and shows how CAS theory can be usefully applied to better understand the behavior of products in rapidly changing markets.

Based upon this understanding, a method for rigorously structuring product design problems based on a well–defined set of constraints common to all design–related disciplines is proposed. This constraint framework contributes to design education and practice by providing a scaffold for transdisciplinary instruction and communication with regard to the complexity of

product design processes. Finally, this work presents an Excel-based software tool to assist design teams in applying constraints and complexity concepts to design problems. Based on existing matrix modeling methodologies (Design Structure Matrix, House of Quality, etc.), this tool tracks constraint interactions and trade-offs in order to help designers anticipate potential failures, and identify innovative opportunities. This tool was developed and tested in a senior/graduate level course in product design engineering at the Ohio State University. The two conducted studies attempt to assess the impact of the tool on many aspects of the design process including teamwork, design outcomes, creativity, utility, and communication.

When utilized in tandem, the constraint framework and the constraint tool can increase the conceptual and practical accessibility of the complexity that underlies every product design process. If used appropriately, these methods provide a platform for understanding, exploration, and design that can help designers of all types to develop solutions that are better aligned to the constraint environment that characterizes their unique design contexts.

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Publications

P. Scudieri, Information in Complex Product Systems, M.A. thesis, Design, Ohio State, Columbus, OH, 2009.

P. Scudieri and C. Gill, "Giving the Product a Voice: Users and Information in Sustainable Systems," in Proceeedings of the 10th International Conference on Engineering and Product Design Education, Barcelona, 2008.

P. Scudieri and B. Lilly, "A Constraint Based Model of the Design Process," in International Conference on Engineering and Product Design Education, London, 2011.

Fields of Study

Major Field: Industrial and Systems Engineering

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Chapter 1: Introduction

1.1 Summary

This dissertation will address the general area of design theory and in particular, product design theory. Previous work in this area has been primarily concentrated in various specific fields of design; this dissertation seeks to broaden the focus of design theory in order to apply it to the design and evolution of complex engineered products. The dissertation will present a solid theoretical background grounded in engineering design theory, as well as elements of complex adaptive systems, design constraints, product architecture, and design evolution. The theory is specifically intended to enable the design of products for rapidly changing markets. It will also provide the basis for a new design tool, derived from the Design Structure Matrix network modeling methodology that will enable design teams to apply the expanded theory to specific product solutions. This tool has been developed, prototyped, and tested in a senior/graduate level course in product design engineering at The Ohio State University. The hypothesis of this study is that the use of the tool, in comparison to pre-existing methods, will provide benefits with respect to: engineering design education, design team work and communication, anticipation of failure points, recognition of innovative opportunities, and quality of solutions. The results of these tests will form an integral part of the dissertation.

1.2 Background

This dissertation is preceded by a significant body of literature in engineering design theory. In the past, design theory has characteristically emphasized specific application areas. As a result, previous work tends to be narrowly focused, for example, on engineering (e.g., Suh's *Axiomatic Design* [1] and Pahl & Beitz's *Engineering Design: A Systematic Approach* [2]), architectural design, or industrial design (e.g., Jones's *Design Methods* [3], Alexander's *Notes on the Synthesis of Form* [4]). Even works ostensibly geared toward product design, for example Pugh's *Creating Innovative Products Using Total Design* [5], or Ulrich & Eppinger's *Product Design and Development* [6],

are typically slanted toward a single discipline. However, relatively little has been written that attempts to unify these various design 'silos' in a way that is actually useful for practicing product design teams, which are inherently interdisciplinary. As a result, the various disciplines that typically participate in the design and fabrication of complex products often struggle to find common ground to understand, or even discuss, each other's design methods, assumptions, and worldviews.

1.3 Relevance

A significant percentage of engineering research is geared towards the development and fabrication of physical products and artifacts. Unlike pure scientific research, which is often focused purely on the expansion of knowledge, engineering research derives its value with respect to its application; it is fundamentally about creation and contrivance. With respect to the creation of physical artifacts and systems, all engineering research is valuable only insofar as it aids engineers to design, construct, and maintain structures, systems, and processes that fulfill an intended function. Most engineering research is not intended to be self-important, but rather valuable as a part of some broader contextual application. Accordingly, the act of design provides structure and purpose to engineering research; it allows engineers to answer questions about what an artifact is, why it matters, and what aims it will serve. Design determines the manner in which advances, derived from engineering research, will be brought to bear within a specific context.

The specific real-world contexts for which engineers develop solutions, however, are inherently complex. As a result, the actual relevance of an engineering solution is defined much more broadly than the scope of most engineering research, which typically requires the isolation of a single research question that can be concentrated on at the exclusion of all else [5]. Because of this focus on highly specific problems, typical research can sometimes predispose engineers to developing the "wrong system right" [7]. That is, developing an artifact whose component parts are rigorously understood and optimized while neglecting an artifact's larger value and usefulness. This often occurs as a result of a complex set of factors originating from a wide variety of contexts and origins. Accordingly, real-world product design processes are characterized by the need to balance a complex set of constraints which define the product's performance. A product's design is influenced by constraints that arise from manufacturing, use,

technology, and market concerns; and successful solutions must skillfully balance all of these factors. As a result, all of the modeling, optimization, formal mathematical techniques, and deterministic methods in the world cannot save an artifact that is poorly conceived with respect to its purposes and context.

The actual practice of engineering design, and any research on engineering design, must tackle this complexity, as well as question each artifact's purposes and functionality. Doing so, however, often requires the expertise of individuals from a variety of disciplines; it is not unusual to see the efforts of multiple engineering disciplines, industrial design, business, marketing, etc. all represented in a single product. As a result of the multi-faceted and interdisciplinary nature of design, research on engineering design is challenging and inherently imprecise. That in no way makes research on the design of artifacts unimportant, or unnecessary. In fact, because of the desire to apply knowledge in order to achieve a set of goals, research on design is becoming increasingly relevant to the practice of engineering. It is important to note that this dissertation is not positioned in opposition to current engineering research methodologies or practice. Instead, one of the goals of this dissertation is to position engineering design research alongside more traditional engineering research. By focusing on engineering design research, it is possible to amplify the value of traditional research by ensuring that the more highly specified research finds appropriate application in relevant, useful, and highly considered artifacts.

1.4 Structure and Contribution

This dissertation makes an original contribution in the area of product design theory. It presents a framework, grounded in an extensive review of the literature in design, complex adaptive systems, and product architecture that can be applied to complex product systems. The general structure is as follows:

Chapter (2) Situates products and contemporary product design in the larger field of complex adaptive systems (CAS), and shows how CAS theory can be usefully applied to better understand the behavior of products in rapidly changing markets. This chapter establishes the background and context, and many of the concepts outlined in this chapter will be revisited throughout the dissertation;

Chapter (3) Develops a method for rigorously structuring product design problems based on a well–defined set of constraints common to all design–related disciplines. The five categories of constraints outlined here contribute to design education and practice by providing a transdisciplinary framework for instruction and communication with regard to the complexity of the product design processes;

Chapter (4) Establishes a holistic view of design with respect to the constraints outlined in *Chapter 3*. The structure of constraints relevant to the design process is discussed, and the concept of biological fitness is introduced in order to help judge the appropriateness of a design solution for a given context and purpose. This chapter also explores the way that the design environment changes over time: technology is changing, the nature of competition is changing, as are the expectations and desired capabilities of users;

Chapter (5) Information about the underlying design constraints and product architecture are recognized as critical considerations when designing for changing contexts. In order to help designers understand and manage this change, current product architecture theory is adapted to provide strategies for designing modular products that can be more readily adapted to changing markets and user demands, thus allowing for shorter design cycles and increasing organizational agility;

Chapter (6) This chapter focuses on the design and structure of a software tool that allows interdisciplinary teams to capture, categorize, and leverage information from multiple stakeholders throughout the design process. The tool is intended to help teams better identify the constraints that exist throughout an artifact system, so that a design solution can be better balanced with respect to the concerns of manufacturing, distribution, clients, users, etc. But constraints do not exist in isolation, and constraints from one area of the system frequently impact other constraints leading to difficult trade-offs and unexpected breakdowns. Accordingly, the tool is designed to track interactions and trade-offs to help designers anticipate potential failures, and identify innovative opportunities. The described approach is intended to be accessible enough to be deployed in practice and educational settings;

Chapter (7) The constraint tool (introduced in *Chapter 6*) has been developed, implemented, and tested at the Ohio State University. This chapter discusses a two-part research study that was conducted in conjunction with the implementation of the constraint tool in an engineering design education context. The structure and results of the study are analyzed and discussed, as are future directions and research opportunities;

Chapter (8) Serves as a conclusion to the dissertation, by positioning this work with respect to the broader field of engineering design. It also connects the dissertation's central elements (original synthesis, constraint framework, and the constraint tool research study) into a holistic method intended to help individuals and organizations better manage the design of physical products within complex artifact systems.

Chapter 2: Design and Complexity

2.1 Introduction

The world we live in is not a simple place. In fact, it is quite complex. Even without looking to the many formal definitions of this term, the complexity of the world in which we live—and the world for which we design—is undeniable [8]. Markets, cultures, governments, people, organizations, technologies, products, and firms all co-exist and interact with one another to produce results and behaviors that are difficult to categorize and track, let alone predict. The rise and fall of any single trend—whether this season's newest fashion or the rise of the personal computer—is intimately tied to a litany of factors that could never be expressly detailed. It is within this complex framework—a world made up of products, users, economies, and market segments—that designers of all types are charged with the task of identifying opportunities and creating solutions.

Recently, the concept of *wicked problems* has gained traction in a number of design circles. Wicked problems are those problems which are difficult to solve because of incomplete, contradictory, and changing information and requirements that often result from multiple stakeholders [9]. Originally theorized in the area of policy planning, Rittel and Weber describe wicked problems as such [10]:

> The search for scientific bases for confronting problems of social policy is bound to fail, because of the nature of these problems. They are "wicked" problems, whereas science has developed to deal with "tame" problems. Policy problems cannot be definitively described. Moreover, in a pluralistic society there is nothing like the undisputable public good; there is no objective definition of equity; policies that respond to social problems cannot be meaningfully correct or false; and it makes no sense to talk about "optimal solutions" to social problems unless severe qualifications are imposed first. Even worse, there are no "solutions" in the sense of definitive and objective answers.

In their original formulation of wicked problems, which appears in *Dilemmas in a General Theory of Planning* (1973), Rittel and Webber put forth ten characteristics of wicked problems.

These characteristics are outlined below, and are accompanied by brief descriptions tailored to our specific interests in product design:

1. **There is no definitive formulation of a wicked problem:** It is not possible to enumerate every possible direction or solution because solutions are dependent upon our understanding, and vice versa.
2. **Wicked problems have no stopping rule:** There are no definitive criteria for establishing when an appropriate solution has been reached, instead design activity typically concludes as the result of external factors (depleted resources of time, money, etc.).
3. **Solutions to wicked problems are not true-or-false, but better or worse:** There is no right answer to a design problem, but there are still good and bad design solutions.
4. **There is no immediate and no ultimate test of a solution to a wicked problem:** We cannot definitively state the value of any design solution, which is evident in the inherently subjective and fickle nature of design evaluation.
5. Every solution to a wicked problem is a "one-shot operation"; because there is no opportunity to learn by trial and error, every attempt counts significantly: It is impossible to judge the *true* effectiveness of a design until it is released, but doing so carries significant costs.
6. Wicked problems do not have an enumerable (or an exhaustively describable) set of potential solutions, nor is there a well-described set of permissible operations that may be incorporated into the plan: It is not possible to account for every potential solution to a design problem, and as such design cannot be considered an optimization problem.
7. **Every wicked problem is essentially unique:** While containing similarities to other design problems, each design process is in one way or another unlike all of the problems that have come before it.
8. **Every wicked problem can be considered to be a symptom of another problem:** Design problems are composed of many smaller problems, and address larger problems in the lives of users.

9. The existence of a discrepancy representing a wicked problem can be explained in numerous ways. The choice of explanation determines the nature of the problem's resolution: The way in which designers frame the problem directs the solution, and as a result different designers will arrive at different solutions.
10. **The planner has no right to be wrong:** The goal of design is not to find truth, but rather to improve some aspect of the world; accordingly, designers are liable for the consequences which they generate.

In design, the use of the term 'wicked problems' has typically been restricted to large-scale problems in the realm of economic, environmental, and political issues. Using design to affect poverty, hunger, social issues, climate change, sustainability, and health and wellness are a few tasks typically referred to as wicked problems [11], as their resolution requires that designers affect a large number of people in a variety of contexts. But in reality, *all* design problems are "wicked" when viewed from a particular perspective, or at an appropriate scale. The elements that comprise a product system (artifacts, design organizations, clients, users, manufacturers, cultures, markets, etc.) interact in non-linear ways to produce the behavior of the overall system. As a result, successful solutions must balance factors that arise from throughout this space. Essentially, all design activity is challenging and uncertain because all design problems are "wicked," when considered in light of the complete product system. Glance back at the list of characteristics of wicked problems, and one is likely to find that these elements accurately describe almost any design process. This is a result of a property called *complexity*, which underlies the systems in which all artifacts are designed, fabricated, and used.

If one considers even the simplest products as one element embedded in larger human systems, wickedness and complexity always follow; everything is related, deeply intertwined. The development of a new product yields many unknown consequences across a product's fabrication, adoption, and use. Within product systems, there are so many moving and interacting pieces that no design organization can accurately see into the future in order to predict market direction, or even the success or failure of a single product. In contemporary global markets, competitors quickly learn from and adapt to each other's products in order to

develop new designs which provide increased capabilities to users, who in turn expect new features from future products.

At the same time, advances in technology enable new levels of product functionality that go far beyond what the typical consumer could expect. Users themselves make purchasing decisions based upon trends and expectations informed by products and designs that they have previously interacted with, before applying and adapting these designs in inherently novel ways to meet their changing goals and needs. In order to be successful, every design must satisfactorily balance these many factors, which arise from many stakeholders and points throughout the system. The unique constraints of each design problem, in combination with the interactions that occur among these elements lead to the difficulty of developing successful products—it is often claimed that only 15% of new products actually succeed in the market. This ultimately yields a constant stream of new designs, and a very real struggle to manage products, platforms, and technologies over time in the face of dynamic markets. Because we can never escape this complexity, almost every design problem meets the criteria to be considered a wicked problem.

In many ways, using the term 'wicked' to describe design problems is merely a useful way to indicate that design is a complex activity, and artifacts exist within *complex systems*. Complex systems are, roughly, systems whose behavior cannot be reduced to a single cause or explanation as a result of the interactions among its elements—they typically exhibit properties and behaviors not apparent when viewing their parts in isolation [12]. They are non-linear systems that exhibit a great deal of tension and fluctuation as they interact with the rest of the environment, and frequently exhibit mutual causality and non-predictable emergent outcomes [13]. The study of complex systems is a rich field that stretches across a number of disciplines ranging from economics and mathematics to evolutionary genetics and biology. This diversity of application is only possible because of the shared structures and patterns that characterize *all* systems, and produce a set of common phenomena regardless of the specific context. The study of complex systems is well established and not only predates the idea of wicked problems, but also offers a wealth and depth of research that stretches well beyond what the literature on wicked problems can offer. Conklin, Basadur and VanPatter note [14]:

> Today there is so much hype around wicked problems that it would be easy to overlook the preceding history and the fact that the rising complexity of problems had been identified as an issue by the problem solving/operationalizing thinking

> community for some time—twenty years before *Dilemmas in a General Theory of Planning* appeared.

This is not to say that Rittel and Weber's formulation of wicked problems is without value, as they distinguished a new domain of problem type and brought awareness to the issues of complexity which characterize many types of problems. Still, it is more beneficial to look to the study of complexity and complexity science to gain a deeper understanding of the design process, and a more realistic picture of design performance. The goal of this chapter will to be to move towards an understanding of the effects of complexity on design, and to establish a framework for thinking about *complex product systems,* which we will define as irreducible systems comprised of artifacts, individuals (designers, manufacturers, users, etc.), contexts and activities, whose behaviors arise as a result of the non-linear interactions of these parts. Complex product systems are characterized by a great deal of uncertainty, and exhibit a set of behaviors and relationships that are all but guaranteed to change over time. The structure of complex product systems is at the core of what makes it challenging to identify appropriate design directions, predict the success or failure of artifacts, and understand how designs will be adopted or used once placed in the context of use.

Rather than simply taking the complexity or "wickedness" of a design problem as a given, this chapter will seek to explore the structures that underlie complex product systems so that we can move towards strategies and understandings that will help organizations to develop products more appropriate to their goals, more in line with users' desires and expectations, and better fit to the actual state of the system. The influence of complexity on designs, designers, and the design process is a vast, but under-discussed, topic within design literature and related academic fields, and the intention of this chapter is to explore the intersection between complexity and design in an authentic and meaningful way. The concepts, patterns, and understanding established in this chapter will serve as a context for exploration throughout the duration of this dissertation, as it establishes the background and subtext that will provide meaning to the rest of this work. Accordingly, many of the ideas outlined in this chapter will be revisited and reapplied throughout the remainder of the dissertation.

This chapter will also provide an overview of the ways in which the formal study of complexity applies to the context of design. It will begin with an overview of complexity, and an

exploration of the various senses in which complexity is discussed and used. This will be followed by a discussion of the applicability of complexity in the context of artifact design. After providing a basic understanding of how designed artifact systems can be viewed as complex adaptive systems, the underlying structures of complex systems will be explored. The chapter will conclude by attempting to integrate these concepts in order to construct a cohesive understanding of complex artifact systems. A specific focus will be placed on the challenges that complexity imposes on the designer and the design process; ultimately moving towards a more complete understanding of product systems, and suggesting potential ways to overcome the difficulties associated with complexity.

2.2 A Larger Unit of Design

Designed products do not exist in isolation, insulated from the effects of their surroundings; economies, jobs, competing products, and user responsibilities all have some bearing on an artifact, its use, and its success or failure. The artifacts that designers create are produced by manufacturing firms and sold by retailers, but even once in the hands of the "user" the product is subject to factors that stretch well beyond what most would define as that object's intended usage. As a result, every design must serve the goals and needs of its users in some larger context. Design is not merely about specifying the number of screws or the physical dimensions of a tangible object—if it were, design would be a linear and uncomplicated task. Rather, designers are tasked to satisfy users' desires and support users' goals within the context of their lives and activities [15]–[17].

A great many authors, from a variety of backgrounds, have recognized the idea that designs exist in order to support people. In many ways, a number of design approaches and methodologies implicitly recognize the importance of this idea: user-centered design focuses on the understandability and usability of artifacts by thinking like a user [18], [19]; ethnography stresses understanding the role of the user and their relationships to tasks and artifacts [20]; and participatory design includes the user as co-designer with the intention of better understanding their ideas, emotions, and aspirations [21]. Then, there are also a number of authors who explicitly recognize, and deliberately explore, the role design plays within a user's life, activity, or context. In their book *Understanding Computers and Cognition*, Terry Winograd and Fernando Flores

point out that designs are additions to pre-existing networks within the user's on-going field of activity [17].

The fact that designers are creating objects to fit into the lives of users—who have pre-existing goals and responsibilities that will continue to exist after a new design—is an important idea that is echoed by J.M. Carroll. Carroll suggests that designers are chiefly concerned with design at the level at which "…tasks become meaningful to the people who engage in them" [15]. His implies that the artifact itself has a diminished importance in comparison to the role the artifact plays with respect to the user. This may seem like a subtle difference, but its importance cannot be overstated. The only reason an individual, or an organization, purchases or uses an artifact is for some purpose, within a particular context—a telephone is useful only insofar as it facilitates communication, just as a stapler allows for the attachment of multiple pieces of paper, and a tea-kettle heats water to be used for some purpose. While these examples are all simplistic, they effectively illustrate the product's role as a conduit for functionality—the product itself is just one way to connect a user to a desired capability, goal, or outcome.

To D. Woods, the ultimate goal of design is to "…support cognitive work" [7]. While Wood's focus is on the design of complex artifacts, such as airplane cockpits, nuclear power plant controls, robots, and other joint-cognitive systems, his position extends to simpler artifacts as well. Every design and every artifact is meant to support human activity: Graphic designers develop visual representations intended to support human understanding and communication; industrial designers develop physical artifacts intended to provide utility and pleasurable experience; and engineers develop artifact systems like engines and airplanes that extend human capabilities—locomotion and air-travel, for instance. This same logic can be applied to every field of design, whether that is software design, architecture, or human computer interaction. Designs cannot exist apart from the goals, responsibilities, and purposes of the individuals who use them, nor can they exist apart from the demands and pressures of the context in which they are applied.

The notion that designs exist in order to support the goals and needs of individuals relies upon the recognition that designs are, in fact, part of a larger context or network. It is only at the intersection of the artifact and the surrounding environment that a design can find meaning and value in the ongoing life of a user. Christopher Alexander describes this as the intersection of 'form' and 'context,' saying that, "when we speak of design, the real object of discussion is not

the form alone, but the ensemble comprising the form and its context" [4]. J.M. Carroll advances the idea of a task-artifact framework [15], and James Fleck similarly looks at the unit of interest as the artifact-activity couple [22]; stating, "not the artifact, nor the idea, nor the organization as a whole, is adequate by itself as the unit of analysis. 'Technology in use' is an amalgam of artifact, knowledge and organization. [It is] a dynamic ensemble of the artifact with the *immediate set* of human activities that sustain the use and development of the relevant technology."

Woods and Roth broaden this understanding even further by recognizing three interconnected elements in any cognitive system: the artifact, the field of practice, and the human agent [23]. "The basic unit of analysis and design in cognitive engineering is a cognitive system, composed of interacting human and machine agents in a work setting. For example, in software design, the software cannot be evaluated independently of the tasks that the user needs to perform or how users will interact with the software to accomplish the tasks" [24]. While not expressly developed for product design, the basic applicability of these categories is evident in that one cannot view a product independently of the user or the context—which encompasses both the environment of use and the activity or task for which the artifact is relevant.

The concept of a *larger unit of design* is composed of the artifact, the user, and the context, and is essential to understanding the effects of complexity on product systems. While it has been addressed by a variety of authors, its recognition is not limited to theorists, academics, and authors. Design practitioners, too, recognize this larger unit of design and its impact on design performance. While not always explicit, the importance of these interacting factors is inherently recognized in many design methodologies and paradigms, and can be closely correlated to the concept of the 'user experience.' At its core the 'user experience' is dependent upon the dynamic relationship that exists between people, objects, and contextual factors such as time pressures and environmental conditions. In talking about designing experiences rather than products, IDEO's Jane Fulton-Suri recognizes that the value of a product is dependent upon its ability to support user tasks and serve a purpose. She also states that, "people will have experiences with the things we design, whether we intend them or not, and in ways that we cannot hope entirely to predict" [25].

In saying this, Fulton Suri points out that whether or not these interactions within the larger unit of design are recognized, their impact on design performance is unavoidable. The larger unit of design will always have its say. Viewing any part of the larger unit of design in

isolation (focusing solely on the artifact, the context, or the user), will never allow designers to adequately characterize the product system. Even focusing on the intersection of two of the three factors can yield an unrepresentative understanding. Focusing on the intersection of the artifact and the user can yield beneficial insights about interactions and interfaces, but use in context also influences the value, role, and performance of an artifact in ways that are not apparent when only looking at the other two elements. And a lack of simultaneous consideration for the entire larger unit of design is often responsible for the failure of real-world products.

The design of a new medical device, for instance, must be concerned with a nurse's ability to understand and interact with the device in order to perform a useful function or provide practical capabilities. But even if designers manage to achieve these things, the device is unlikely to succeed if it does not balance pressures and demands that only become apparent in the larger context. Within every hospital context, relentless time pressures, patient safety, highly specified procedures, and patient data collection are omnipresent considerations that exist outside of the boundaries of any particular task. Even great designs (from the perspective of the artifact-user interaction) are unlikely to be successful if they fail to recognize the role of context in determining both user and product behavior. As just one example, a bariatric lift intended to help turn and lift obese bed-ridden patients is not likely to be successful if it requires excessive set up times. While the device may help nurses to manage the patient's weight, the long set up would further increase the time pressures on the nurse and would likely prevent them from performing other required tasks, which may in turn affect the safety and health of all of the patients under their care. It is only at the intersection of all three factors, within the larger unit of design, that the true nature of the product system becomes apparent.

Looking at the various ways in which these authors provide recognition to the important interactions between users, context, and design provides a sense of the importance of the larger unit of design, but little consensus on how exactly it ought to be described. But settling on a single nomenclature is not important, nor is it critical to the actual practice of design. What is important, however, is that this larger unit of design, and the relationships that exist across these elements is what introduces complexity into product systems: a user's goals and needs are shaped in response to the activities, demands, and desires present within a particular context, and as such, artifacts cannot be designed or evaluated independently. The artifact, its users, and the contexts in which it performs all affect one another in highly dynamic non-linear ways, giving

rise to complex product systems that will change and adapt in unpredictable ways. This complexity has always been an integral part of designed product systems, but as a discipline, design is only now beginning to recognize the ways in which this complexity shapes design thinking, the design processes, and the performance of designed solutions. The complexity that results from the larger unit of design is at the heart of what makes the activity of design challenging, open-ended, and multi-faceted. It is also what makes design such an enjoyable, intellectually stimulating, and ultimately rewarding activity.

2.3 Complexity

Because of the interconnected nature of product design, it is logical to look to the study of complex systems as a field with potential relevance for understanding and managing product development processes. As complexity is inherent in the world, there is a great deal of ongoing research on complex systems and their phenomena within a variety of scientific fields: mathematics, biology, ecology, genetics, economics, sociology, engineering, and computer science just to name a few. While each field chooses to emphasize different aspects of complexity base, the central tenets of complexity remain: regardless of the specific field, the study of complex systems is driven by the desire to understand the phenomena which emerge from a collection of interacting elements [26].

To offer a starting definition of complexity, we can refer to Herbert Simon—Nobel Prize recipient, and one of the forefathers of complexity science—who defines a complex system in this way [27]:

> Roughly, by a complex system I mean one made up of a large number of parts that interact in a non-simple way. In such systems, the whole is more than the sum of the parts, not in an ultimate, metaphysical sense, but in the important pragmatic sense that, given the properties of the parts and the laws of their interaction, it is not a trivial matter to infer the properties of the whole.

In this definition, Simon identifies the key components that give rise to complexity: *Complex systems* are systems composed of interconnected parts that exhibit behavior not evident when studying the parts in isolation. As a result, the behavior of a complex system is difficult to simulate, and nearly impossible to predict fully—something that is evident in product systems as

the interactions of designers, users, organizations, competitors, manufacturing technologies, etc. give rise to unpredictable system performance.

The study of complexity is a still emerging field, and as a result 'complexity' and 'complex systems' can be difficult terms to define in a rigorous and accurate way. First, the term 'complexity' embodies a large number of related concepts, and, as a result, it often feels as if all of the relevant concepts and theories need to be explained simultaneously in order to impart any sort of authentic understanding [8]. Secondly, the term 'complex' is often confused, and used interchangeably, with the term *complicated*—particularly colloquially. *Complicated systems* are difficult to understand, and often the result of a large number of elements [28]. Roughly, a complicated system is messy and hard to understand because it is a complicated assembly of a large number of *discrete* parts. Conversely, *complex systems* are composed of highly interdependent elements and subsystems governed by a set of shared rules. As a result, the behaviors of complex systems are highly dependent upon the relationships and interactions that exist among its component parts.

Complicated systems can be decomposed and recombined without a loss of function. Newtonian mechanics and basic systems engineering principles, for instance, are reliant upon viewing the world as a complicated system [29]. Each decomposes a system, and attempts to build an understanding based upon the individual pieces—system performance is the summation of each of the parts. Newtonian mechanics for instance breaks a physical system into its component parts, forces, and interactions, and builds a general understanding of the system based upon these elements. When complex systems, on the other hand, are broken down into their component parts the system behavior can no longer be understood in an authentic way; complex systems cannot be understood as a sum of their individual pieces. Ant colonies, weather patterns, political systems, economic markets, and socio-technical systems (like the internet) are often cited examples of complex systems as their system-level behavior cannot be described based upon an understanding of their individual parts viewed in isolation. The seemingly sophisticated behaviors of ant colonies cannot be understood by studying an ant, just as the explosive growth and power of the internet cannot be understood as a linear combination of computers, individuals, and communication infrastructure.

If product systems were merely complicated, instead of complex, it would be possible to reduce a system to a basic unit of understanding—such as the product, the user, or the design organization—and use that unit to describe the system through a series of linear relationships.

Eventually, we could build a complete understanding of how a product system functions and changes over time, based upon a series of causal relationships. That understanding could then be used to definitively describe the reasons for a product's existence and performance. Design organizations, for instance, could identify specific market indicators that would point to (and guarantee the success of) particular products; and when a product did fail, designers could authoritatively name the reason. Although not easy to achieve, in a complicated system this understanding could be extended to accurately predict the success or failure of products, and the subsequent movements of entire markets.

Clearly, understanding product systems in such a definitive way is not possible. Real-world product systems cannot be described in any sort of causal linear way. This is because the behavior of product systems arises based upon the unpredictable interactions of humans, products, organizations, and cultural constructs. It is also the reason why we must refer to product systems as *complex*, rather than complicated. A complex system cannot be understood using a linear, reductionist approach, despite the fact that its parts may seem simple in isolation. Complexity looks at the interactions of the systems parts—rather than the parts themselves—as the element that drives the behavior of the system. But as both complicated and complex systems can have interacting parts, it is the way in which a system's components influence the behavior of one another, and the system as a whole, that differentiates the two [16]. This essentially adds what John Miller and Scott Page call an interdependence requirement to the definition of complex systems [30]; and it is this interdependency between elements that makes a system complex. Essentially, the elements of complex systems can never be viewed as unconnected from the rest of the system elements. In this way, complex systems can be seen as the opposite of independent, while complicated systems are the opposite of simple [29].

A product, viewed in isolation, can often be viewed as a complicated system, rather than a complex one. A mechanical pencil is composed of a number of interacting parts—the lead, the eraser, the pocket-clip, the body, and the central shaft that, when depressed, advances the lead. But removing the eraser or the grip only makes the pencil less complicated—there is one less element in the system. Removing the lead from the pencil would cause the pencil to no longer function as intended, but as a result of the linear interactions this behavior is perfectly predictable and immediately understandable. The pencil's failure to perform can easily be traced through the system. At the same time, recognizing that products do not exist in isolation, but

rather as parts of a system that includes users and contexts, even simple objects quickly become 'complex'. Changes to just one part of the system—the shape or size of the pencil's lead, the shape and form of the pencil, or the way in which users wish to record information in concert with new digital technologies—can cause unpredictable interactions between components within the artifact system. These unpredictable interactions can either fade away—hardly altering the system at all—or propagate throughout the system causing massive change [16]. But the truth is that we cannot know in advance the exact impact that any change within the system will have. A change in users' goals or desires may lead to changes to the artifact – just as changes to the artifact may lead to unexpected uses, or the artifact being used in new contexts, for new purposes.

The unpredictability and change inherent in product systems can be traced through almost any series of artifacts, but some of these principles can be illustrated by tracing the evolution of one particularly iconic artifact: the Swiss Army knife. Since the introduction of its first precursor in 1891, the Swiss Army knife has spread across the globe, and its design and functionality have impacted generations, cultures, and other multi-tools—evidenced by the addition of the knife to the permanent collections of the New York Museum of Modern Art and the Munich State Museum of Applied Art. Originally produced for the Swiss Army in the late 1880's under the name *Modell 1890*, the knife was designed to open canned food and disassemble the Swiss service rifle, the Schmidt-Rubin M1889. This original incarnation included a blade, a reamer, a can opener, and a screwdriver that all folded out from the same side of a dark wooden grip [31].

Figure 2.1: The original one-sided Modell 1890 with dark wood grip, and the 1897 incarnation.

In 1891, Karl Elsener took over production of the Modell 1890, and began producing the knives at the cutlery workshop he opened in Ibach-Schwyz, Switzerland with the support of his mother, Victoria. Not satisfied with the original incarnation of the tool, Elsener immediately set out to redesign it. After five years of work, he managed to add a smaller cutting blade and a corkscrew to the tool using an innovative new spring mechanism that simultaneously held in place blades on both sides [32]. By the time Elsener had released the next incarnation of the tool in 1897, the wooden grip also changed to the now iconic red color—a change rumored to be the result of soldiers' difficulties finding the knife after it had been dropped in the snow [33]. Elsener continued to produce these knives in Switzerland under the Victorinox banner—a combination of his mother's name and "inox," a shortened version of the French word for stainless steel "inoxydable" [34]. But it was the end of the Second World War that ultimately launched Victorinox and the Swiss Army knife as a global brand, as American soldiers—who could purchase the knife at PX stores—returned home with the knives en masse [35].

The durability, portability, and multi-purpose functionality quickly led to the knife being introduced into a wide variety of different contexts (ranging from military application to consumer use), which ultimately resulted in the demand for new capabilities. Toothpicks, eating utensils, scissors, saws, nail files, compasses, and a wide array of other new tools quickly followed as the Victorinox brand continued to grow. Over the years technology and global culture has continued to change, and the demands and desires of users have changed in step; while the Swiss Army knife's basic design has remained intact, its individual features have changed to reflect the times.

The evolution of culture and technology apart from the knife has also led to new features, and it is not uncommon to see features such as USB drives, laser pointers, Bluetooth connectivity, etc. While this knife bears a striking resemblance to the earliest Modell 1890, the changes that have occurred over the past one hundred plus years have been considerable. But these changes have occurred in ways that would have been thoroughly unpredictable at the outset—a result of the co-evolving interactions and demands that exist between users, designers, and the ever-expanding activities in which they are engaged.

Figure 2.2: A current Swiss Army knife that contains all of the tools necessary for both the digital and analog world.

Once again considering the larger unit of design—comprised of the artifact, the users, and the surrounding context—further expands complex systems into what are called *complex adaptive systems*. The inclusion of the human element brings with it *adaptive capabilities*. Users make choices about everything from which products to buy to what to use products for, and can adapt their behavior based upon changing needs and desires. They bring to the artifact system the ability to learn and change. But end users are not the only adaptive units within a system, and designers, firms, and corporations must also be considered adaptive agents; as each has the ability to alter their behavior in response to the larger artifact system. As the result of these interdependencies, new behaviors emerge and in response, designers adapt to shifts in the market and perceived needs and opportunities in the lives of users. This produces a constantly churning artifact system in which artifacts and products are changing in conjunction with users and uses, amidst the background of dynamically changing contexts. In our Swiss Army knife example, the soldiers, designers (Elsener), manufacturing firm (Victorinox), and eventually consumer users (soldiers, campers, consumers, etc.) are all adaptive agents who have had some bearing on the evolution of the knife's design.

In a complex adaptive system, when one element of the system changes, it influences many other elements as the result of the system's interdependencies and the ability of those elements to adapt. At the level of the whole system, many adaptive units are simultaneously adjusting their behavior based upon the behavior of the other units within the system—with each unit changing in order to meet goals and needs at its own local level [16]. Users, for example, do not typically alter their behavior with the company in mind; they do so to meet their immediate needs and desires at their own local level. This sort of behavior is common in the

biological world, and one can think of the co-evolution of species as an illustrative example of a larger class of complex adaptive system [36]. This mutually influential behavior can occur in a supportive way, as in the case of the co-evolution of flowering plants and their pollinators; or in a classic competitive way, with predator and prey each evolving to stay ahead of the other. Elsener's invention of a new spring mechanism allowed the inclusion of more tools, providing additional capabilities to soldiers in the field. But these new capabilities triggered new expectations and desires in its users—a desire to find the knife in the snow, or open a corked bottle—which led to subsequent changes in the knife's design.

What all of this illustrates is that artifact systems, when viewed as a larger unit are, in fact, a specific class of complex adaptive system. The key components (users, artifacts, and contexts) interact with one another to give rise to new artifacts, behaviors, and uses that would be highly unlikely to arise independently of one another. Similarly, changes to one part of the system—changing the design of a physical product for example—often result in changes to users' behaviors, goals, capabilities, and expectations. Those changes, in turn, incite change for not only the original design, but also every other design that comes after it—ultimately leading to never ending cycles of product evolution.

2.4 Components and Attributes of Complex Systems

Looking at our examples, and even stretching back to Simon's definition of complex systems, there are two factors that we can glean as critical to the complexity of product systems: adaptive agents and interdependencies.

2.4.1 Adaptive Agents

Adaptive agents are the basic building blocks of all complex adaptive systems. They are the entities within the system that have some ability to process information and as a result, adapt their behavior. Adaptive agents interact with objects, other agents, and systems, and in doing so create the unpredictability and change within complex adaptive systems [12]. By definition, agents must have some level of autonomy. This is not to say that they are necessarily human; intelligent software, animals, and robots can all be considered adaptive agents, as each has the ability to independently make decisions and take action. At a larger scale, corporations, firms,

organizations, and governments also possess the ability to make autonomous decisions. Agents adapt and act within a larger complex system.

Looking specifically at product systems, it is easy to view users as the primary adaptive agent—as they make decisions about which products to purchase as well as how to apply a design within their particular field of activity. If a design is no longer meeting their needs or if they perceive an opportunity for better performance, the user has the ability to adapt the product or the task as they see fit. They can also purchase and employ a new product altogether if it promises to perform a given task more adequately, in their given context. Apart from the user, the designer is an adaptive agent attempting to anticipate the needs and desires of users. Where they identify needs or opportunities they have the ability to devise new products; where they identify challenges and problems, they can change or update existing designs in order to satisfy the changing system.

While users and designers are certainly adaptive agents, one must be careful not to view these individuals in isolation by defining the system in an overly narrow way. Every user has a network of people with whom they interact. A single user's tasks, activities, responsibilities, and goals are influenced by families, friends, neighbors, and co-workers, as well as factors such as advertising and social media. Each of these has the ability to affect some aspect of product adoption or use. Additionally, there is a network of individuals who are responsible for the manufacture, sale, and maintenance of the design. At a larger scale, the firms, retail companies, and governing organizations that are responsible for the commission, design, manufacture, and regulation of an artifact all influence the ultimate behavior of the system as well. These larger entities are also frequently responsible for delivering physical products to adaptive agents at the lower system levels (firms design and manufacture products for users). Their influence on the product system, while often overlooked during the design process, is clearly crucial to the success or failure of the product.

The behavior of the entire product system emerges from the collective, and mutually influential, interactions of these adaptive agents. The development of the Nest thermostat is an effective illustration of the impact adaptive agents, of all types, can have on the design of a product, its implementation, and the direction of larger markets and product systems. The Nest thermostat is billed as the world's first "learning thermostat," and was designed as an attempt to innovate a technology that had not seen much change in decades. The Nest thermostat was

originally conceived when Tony Fadell—a former Apple executive who helped to develop the original iPod, and who led iPod and iPhone—recognized the opportunity to reinvent this piece of technology. After considerable analysis on existing thermostats and the industry, Fadell and Matt Rogers (another Apple employee) decided to co-found Nest Labs.

Figure 2.3: The performance of the Nest Thermostat and the surrounding system is driven by adaptive agents.

The independent decisions and actions of agents ranging from designers, engineers, and experts at Nest Labs, to the external venture capitalists that funded the project, helped Nest to explore the design problem and shape the direction of the product. The Nest thermostat itself is a sensor-driven, Wi‑Fi-enabled, learning, programmable thermostat, intended to reduce energy costs and improve user comfort along a number of dimensions [37]: The first thing one notices when approaching a Nest thermostat is its distinctive appearance, particularly when compared to the gray and white boxes of thermostats past. It has a domed glass screen intended to reflect the color of the wall, that turns on when you approach it. It glows orange when it is heating and blue when it is cooling. The Nest's screen displays how long it will take for the house to reach the set temperature; a feature intended to save energy by dispelling the notion that the house will heat or cool more quickly if you "crank up" the temperature (in reality, cooling occurs at the same rate whether the thermostat is set to 68 degrees or 50 degrees). Additionally, the Nest is Wi-Fi enabled, allowing it to download software updates and be controlled by users through a web or a mobile application. At around $250, the Nest is not cheap, but it is intended to pay itself off in energy costs in less than two years.

Choosing whether or not to purchase a product is one of a consumer user's most critical adaptive actions within a product system. This decision encapsulates the user's perceptions about

a product and the capabilities that it will afford them, and is influenced by everything from advertising and previous experiences with products to the opinions of other users (friends, blogs, reviews, etc.). The collective decisions of the entire market will determine a product's success, and help to direct future product directions and development as organizations like Nest Labs respond to this user behavior. Beyond choosing whether or not to purchase and install a Nest thermostat, users routinely adapt their behaviors, desires and expectations based upon the product. Once installed, the Nest is likely to affect the way homeowners view their electric bill, their daily routines (when they set the thermostat, how they interact with it, etc.), and what they expect from not only thermostats but household technology in general. The Nest affords families and individuals the ability to change behavior and accomplish new goals based upon this changed technology.

The Nest itself can even be seen as an adaptive agent within the product system—which is one reason it makes for such an interesting example. Unlike traditional thermostat manufacturers, Nest Labs employs a number of specialists in machine learning and artificial intelligence, including MacArthur Award winning Yoky Matsuoka who is the former Head of Innovation at Google. As a result, the Nest thermostat is designed to program itself. Initially, users must set the Nest manually, as they would a normal thermostat (before bed, leaving the house, trips, etc.). Through use, the Nest begins to learn, noting when it was adjusted and what the temperature and humidity were. Eventually, it begins to control itself based upon the household's living patterns. The Nest contains two proximity sensors intended to actually detect the presence of humans, so that it can decide when people are at home and adjust the temperature accordingly, even if the absence is not part of the user's regular schedule. However, turning a product into an 'adaptive agent' does not come without risks: the Nest, like any other adaptive agent, can now make mistakes. One reviewer from the New York Times noted that his "Nests were cuckoo for the first couple of weeks. They'd decide for themselves to blast the heat to 73 degrees—at 4 a.m." He goes on to state that their behavior was initially "…a little alarming. You know those sci-fi movies where our machines turn on their human overlords? Yeah, like that" [37]. In this way, the Nest itself is just one more adaptive agent contributing to the overall behavior of the Nest product system.

Viewed as a complex adaptive system, the Nest product system encompasses a wide variety of adaptive agents, and its direction and behavior only emerge as the result of a non-

linear combination of the behaviors of all its agents. Fadell, Rogers, engineers, designers, and Nest Labs are all adaptive agents exerting an influence within this product system, but so too are investors, retailers, consumer users, and Nest's artificial intelligence software. Each independently assesses the world, makes decisions, and takes action based upon its own perspective and understanding of the surrounding system. Users of the Nest obviously have very different goals and needs (cost savings, comfort, etc.) than do venture capitalists (profitability, return on investment, etc.), but their behaviors each combine with all of the behaviors of the other adaptive agents to determine the performance of the complex product system. Each has the ability to exert some control over certain aspects of the product system (users control the Nest's implementation and use, designers control its features and capabilities, the artificial intelligence controls Nest's learning and heating/cooling patterns, etc.), but the product system's behavior only arises as a combination of these agents' behavior. Adaptive agents, at every level of the system change their behaviors and goals in response to the state of the system, which is largely determined by all of the other adaptive agents within the system.

2.4.2 Interdependencies Lead to Cascading Change and Emergence

Interactions and interdependencies are what simultaneously make complex systems powerful, and impossible to predict with any degree of certainty. Within product systems, the degree of connectedness between the individual components affects the system's performance as well as its complexity, and the system's complexity increases with the number of interconnections. As product systems grow they become increasingly connected, which increases the diversity and potential of the system. These interconnections become the source of new capabilities and opportunities for both users and designers, but those same interconnections lead to difficulties in predicting and controlling the system's behavior—which is what fundamentally makes product systems complex rather than complicated.

In complex adaptive systems, individuals, designers, and organizations all attempt to meet their needs and goals without coordination or any sense of a 'larger goal,' and by doing so new behaviors emerge. As a result, is it is not possible to predict the future make-up and behavior of the system with any degree of certainty. But a lack of foreknowledge does not preclude action, and each agent must still pursue goals and make decisions within this inherently

unpredictable context. Regardless of the particular agent, each attempts to take the 'best' possible action by anticipating how the system will behave in the future. Users attempt to anticipate their future needs, or how a technology will change their capabilities or the activities that they engage in. Design organizations attempt to identify potential opportunities, which are leveraged in order to conceive products that *may* positively impact a user's desires, capabilities, or activities to the point that they are convinced to purchase a product. Doing so requires that designers anticipate the way in which users will interact with the artifact, what it may be used for, and the ways in which the artifact may fail; thus, allowing the artifact to be designed in such a way as to achieve the goals fundamental to the artifact and the user. But designers can never fully predict the performance of their systems, and designs consistently perform and fail in unpredictable ways. According to Simon, it is not possible to accurately predict the behavior of any complex adaptive system, and such systems can only be fully understood after-the-fact: "…to understand them, the systems [have] to be constructed, and their behavior observed" [38].

While we cannot fully predict the performance of product systems, the ability to better anticipate and manage design processes in the face of this uncertainty is one of the primary drivers for studying complexity in the context of product design. *Controlling* the behavior of product systems, then, is even more difficult than *predicting* their behavior. This difficulty of control arises from the fact that as the degree of interconnection grows, simple one to one mappings are eliminated from the system. A single action is rarely responsible for a single result, and a phenomena like 'poor usability' is often tied to a litany of factors ranging from interface design and physical affordances to the user's pre-existing understanding of interaction paradigms. Further, because of the adaptive nature of product systems it is typical for events to cascade through the system. In these 'cascades,' one event leads to adaptations that trigger interactions with the environment or other agents, whose change leads to further adaptations; this continues to the point where the chain of effects from these interactions is difficult to perceive and even harder to predict [39]. Mansfield refers to this as a "wave of effects" propagating through the system [16]. A change to one component within a complex adaptive system is often followed by the effect of that change on other components within the system that adapt to this changed state; which lead to further adaptations in other parts of the system, in turn. This pattern continues like a 'wave' throughout the rest of the system in unpredictable ways.

The effects of this change in product systems can be felt not only by the users, but also by designers in the form of new opportunities, challenges, or a changing design space—to which designers frequently respond with new designs, kicking off whole new cascades of co-adaptive behaviors. In viewing product systems as a complex co-adaptive system one input, or one action, does not lead to a single output or result. Rather, a single input can lead to a large number of diverse outcomes based upon the perceptions and interactions of individual system parts and agents. This leads to a situation in which actions within the complex system produce results and consequences that could not initially be perceived [30]—actions often lead to emergent consequences and behaviors.

Emergence is both a *consequence* and a *characteristic* of complex systems that arises naturally from the interdependence of adaptive interconnected parts. Greater focus will be given to the consequences and influence of emergence on product systems and the design process in the following sections and chapters, but for now we can define emergence as the inherently unpredictable behaviors that arise from a system's dynamically interacting parts [16]. Emergent properties are the unexpected macro behaviors that emerge out of the micro level behaviors and interactions of the elements within a complex system, and thus are a key aspect that differentiates complex systems from merely complicated systems [12].

The phenomena of emergence and emergent system behaviors are present in every type of complex system; from ecological to human systems, emergence is a central theme. It is important to note that, by their very nature, emergent behaviors and properties cannot be predicted or designed for, rather they emerge from the interactions present within the system. Earth's weather systems are one example of system-level emergent behavior as weather patterns and phenomena like cold fronts, rain storms, hurricanes and tornados all emerge from the interaction of relatively simple components—temperature (and temperature transfer), moisture, pressure, etc. [8]. These simple elements interact based upon the laws of physics in order to determine all current and future weather.

As adaptive agents are incorporated into the system, emergent phenomena increase in frequency and the repertoire of possible system behaviors expands. While complex systems may be composed of simple particles interacting according to physical laws, complex adaptive systems replace simple elements with agents possessing some level of autonomy and an ability to process information in order to adapt their behavior. Instead of operating based upon a defined

set of physical or chemical laws, agents learn and react intelligently based upon their goals and perspectives as well as changes in their environment and the actions of other agents. The added complexity of the agents' behaviors gives the system the ability to perform more complicated tasks and leads to the emergence of increasingly complex phenomenon, making the system harder to understand and predict [30].

The natural world offers many examples of emergent behavior. For example, colonies of driver ants exhibit surprisingly "intelligent" behavior by building bridges and nests with their own bodies and coordinating massive migrations across the jungle floor in search of food [40]. These behaviors cannot be understood or explained by looking solely at the system's component parts (individual ants). Instead, these behaviors arise only at the system level as the result of the interactions among individual adaptive agents – the ants – with their environment; the ant colony displays a staggering level of coordination and cooperation. It is possible to see similar behaviors in human systems as well, in the transactions of individual human beings that have grown into an immense world economy that was never centrally planned or coordinated.

Figure 2.4: Emergent behaviors occur across a variety of complex systems: Weather phenomena occur as the result of the interaction of simple elements; ant colonies replace simple elements with agents that can process information; and the behavior of product systems result from the interactions of products, users, organizations, and markets.

Looking towards the realm of product systems, there are many examples in which the seemingly simple interactions of users, products, and other larger systems have led to system behavior that could never have been predicted by looking at individual users or products. A particularly apt example is the Napster music sharing service that was in operation between 1999 and 2001. Napster allowed users to bypass the established music distribution market (compact disc retailers) by copying and distributing MP3 music files across an internet connection. Napster

was initially the result of the interactions of a number of college students and the programming skills of Shawn Fanning, a 17-year-old freshman, but ultimately resulted in accusations of large-scale copyright violations from various sources within the music industry [41]. Napster was ultimately shut down by court order, but not before it had initiated a fundamental change in the way in which recorded music was purchased and used: the introduction of Napster significantly increased the market penetration of MP3 technology and devices, and allowed individual users to develop an understanding and expectations for digital music distribution, storage, and playback.

This burgeoning MP3 market would eventually lead Steve Jobs and Apple to the creation of the iPod MP3 player, and iTunes—a legal and widely implemented MP3 distribution service, that was, by 2008, responsible for 19% of all retail music sales in the United States. That 19% of the market made Apple's digital-only iTunes the nation's single largest music retailer, ranking ahead of both Wal-Mart and Best Buy [42]. The success of the iPod and iTunes was clear evidence of the ongoing restructuring of the music industry, and one of the first glimpses into the future of digital music. The behavior of the entire system has emerged as a result of the dynamic interactions of users, corporations, technology, socio-economic systems, and design. In this way, the unpredictable rise of the digital music industry, digital media distribution, and one of the most culturally relevant products of the new millennium (the iPod), are all connected to a chain of artifacts and events put into motion by the actions of a single college freshman (and other student users distributed about the country). It is also one of a staggering number of new technologies and products that, themselves, emerged as the result of the proliferation of internet access. New designs lead to new needs, demands, and expectations, which lead to new products and even more unpredictable change.

Complex product systems are, by their very nature, constantly changing. As different components within the system—whether that is the design itself, technology, or user preferences—change with respect to time, the adaptive agents learn and adapt their behavior to the current state of the system [43]. This leads to product systems and product markets (systems of product systems) that dynamically evolve as the result of a myriad of interactions among the system's components—products, designers, users, firms, etc. Within this system, complexity shapes every aspect of design—from the design process itself, to the usage of the product within its larger context of application. Whether designers recognize it or not—whether they want it to

or not—complexity affects product design in powerful ways, and emergent behavior is one primary result.

2.5 Attributes and Aspects of Complexity in Design

We cannot discuss complexity in design without talking about scale. Whether talking about the product, the product's embodied components, the design firm, the users, or the entire culture in which the product is embedded, there are multiple scales or levels present within a complex product system. We must not only recognize the existence of these multiple scales, but also the interconnections and interdependencies that exist across them. Products have the ability to affect people and organizations, just as the structure of an organization can affect the design of a product's internal components. The components of a system are never isolated from one another, and interactions and effects frequently occur across scales.

In designed systems there is an impetus to recognize and explore the various scales within a product system. Interactions and interdependencies are not typically isolated within a single system scale. As a result, the behavior of the system is dependent on influences and interactions from scales above and below [16], [44]. For example, the performance of an entire complex product system is dependent upon the behaviors and interactions of users, organizations, cultures and products. But at the same time, even if focused on a single level of the system—the product for example—it is simultaneously affected by all of the system levels above and below it. The decisions of designers, the direction of the company, cultural trends, and desires of individuals who purchase and use a product all affect what that product looks like, how it works, and the roles it serves for all of its stakeholders; just as the product is similarly affected by the components and technologies which comprise it.

Interactions within scales are also quite common, and are generally more easily discerned than those that occur across system levels. Interactions between a product's internal components, for instance, frequently shape the design process and the artifact's performance. In this way, interactions both within and across scales are pervasive, and play a large role in determining the system's behavior. This would seemingly create a situation in which designers need to think about, and simultaneously design for, every part of the system in order to develop a design that is able to successfully balance all of the relevant factors and interactions that occur

at every system level. This would be an overwhelming task, to say the least. Thankfully, cognitively managing this level of complexity is not required in order to design, as designers can avoid the need to concurrently consider every interaction at every scale because of two important properties of complex systems: hierarchy and near decomposability.

2.5.1 Hierarchy and Near Decomposability

If product systems were just one big system, composed of huge numbers of interdependent components, it is not likely that anything would ever get successfully designed. Attempting to solve one part of the problem would lead to cascading effects that would create problems in other parts of the design; which could be fixed, but because of interdependencies, would lead to multiple problems emerging elsewhere. Design would be a never-ending process, in that any attempt to reduce the complexity of the problem would destroy the performance of the larger artifact system. Thankfully, this occurs only if we do not account for the structure of the problem, the design, and the world [4]. In reality, the structure of designed artifacts, and the associated design problems, provides designers with the ability to approach designs in a manageable way that accounts for the interactions and complexity of the system. The structure of artifacts, as well as the systems in which they are used, is one defined by hierarchy—they are hierarchic systems.

A hierarchic system is closely related to the idea of scale, and is a system that is composed of inter-related subsystems, each of which is also hierarchic in structure until we reach some elementary component [38]. In biology, the body can be broken down into systems; which can be broken down into organs; which can be broken down into tissues; which can be further broken down into cells. It is possible to continue this trend even farther, but it is not necessary so long as the elementary unit chosen serves our current analytical purposes. In complex product systems it is possible to look at the hierarchy of the physical artifact, or the social hierarchy [27] in which the artifact is contained.

For the artifact itself, Walter Vincenti states, "One point is fundamental. Design… is multilevel and hierarchical. Interacting levels of design exist, depending on the nature of the immediate design task, the identity of some component of the device, or the engineering discipline." Vincenti goes on to examine one possible representation of an *artifact hierarchy*: he

uses the airplane as his artifact of interest and describes the levels of the hierarchy as follows [45]:

1. *Project definition*—translation of some usually ill-defined military or commercial requirement into a concrete technical problem for level 2.
2. *Overall design*—layout of arrangement and proportions of the airplane to meet the project definition.
3. *Major component design*—division of project into wing design, fuselage design, landing gear design, electrical system design, etc.
4. Subdivision of areas of component design from level 3 according to *engineering discipline* required (e.g. aerodynamic wing design, structural wing design, mechanical wing design).
5. Further division of categories in level 4 into *highly specific problems* (e.g., aerodynamic wing design into problems of planform, airfoil section, and high-lift devices).

The overall design can be broken down into the design of the major components; which can be broken down into subcomponents; which can be broken down into what Vincenti calls highly specific problems. These successive divisions resolve a design problem into smaller manageable sub-problems that can be tackled semi-independently as the result of reduced interactions between levels. But this is only one potential hierarchical breakdown of an artifact. It is possible to construct an artifact hierarchy with subcomponents being combined into components; components combined into sub-assemblies; sub-assemblies combined into assemblies; and assemblies combining to form artifacts. The differences between these two hierarchies lie primarily in their representation, and it is likely that each artifact and each design organization will, in execution, necessitate a slightly different hierarchical representation. What matters is that physical artifacts can be broken down hierarchically, and the resultant implications that this has on the design process.

Viewed at a different scale, it is possible to envision the *social hierarchy* in which the artifact is embedded. This hierarchy could be constructed to include users, designers, and organizations; or it might include users, cultures, and governments. In either case, these social hierarchies are less clearly defined than the artifact hierarchy, but interactions still exist within and between the levels. Effects can spread laterally in the hierarchy, with a user influencing other users; upwards in the hierarchy, with users influencing the design of an object; or downwards in the hierarchy—with companies or designers making decisions that affect users and products

[44]. In many ways, this social hierarchy is tantamount to recognizing the artifact as a part of the larger unit of design, while the artifact hierarchy is equivalent to viewing the product in isolation. The artifact hierarchy allows an aircraft to be broken down into its component parts, but the social hierarchy forces designers to consider the aircraft's broader impacts on pilots, passengers, and a vast interconnected transportation system.

At another scale still, it is possible to look at a *hierarchy of use*, as the artifact's use simultaneously plays out across multiple hierarchical levels of action. Donald Norman in his classic *The Design of Everyday Things* suggests this hierarchical breakdown, and outlines a range of action that stretches from high-level goals all the way down to the very specific movement of muscles that is necessary to accomplish a task. In order to illustrate this, Norman uses the example of an individual driving a car to the bank. While his example is intended to illustrate the difficulty of error detection, he recognizes that, similar to the artifact or social hierarchy, the action being performed can be described at any number of hierarchical levels that combine to make up the entire activity. He breaks up the task thusly [18]:

1. Driving to the bank
2. Turning into the parking lot
3. Making a right turn
4. Rotating the steering wheel clockwise
5. Moving the left hand upward and to the right and the right hand downward
6. Increasing the tension on the sternocostal portion of the pectoralis major muscle

He goes on to describe this hierarchy by stating:

> All these levels are active at the same time. The most global description (the one at the top of the list), is called the high-level specification. The more detailed descriptions, the ones at the bottom of the list, are called the low-level specifications. Any one of them might be in error. It is often possible to detect that the result of inaction is not as planned, but then not to know at which level of specification the error has taken place.

What is both interesting and important to recognize is that there is not one unique version of the hierarchical structure for any complex product systems. Rather, there are alternative structures imposed in order to provide clarity and understand the system. Certainly, there is an actual structure of complex artifact systems, which likely includes all of these

hierarchies, but it is likely beyond our ability to understand and communicate it. These alternative representations, however, all capture some important aspect of the system's actual interactions, associations, and performance. In fact, there is actually great value in being able to define this hierarchy in multiple ways, with each representation allowing us to see a different set of critical interactions or encouraging us to view the problem in a new way.

While this hierarchical structure can help designers to understand the complex systems they design (or design for), Herbert Simon outlines a property of hierarchical systems that is critical to making the design process cognitively and physically manageable. That property is *near decomposability*. In looking at the breadth of interactions that occur within a product system, we can distinguish between two primary types: those interactions that occur *between* levels of the hierarchy—as in the interaction between an artifact and an organization—and those that occur *within* a level of the hierarchy—as in the interactions among an artifact's components. Simon recognized that while both of these interaction types are present in every complex system, the frequency of interactions within a level is generally far greater than those interactions that occur between levels [38]. Simon illustrates this generally [27]:

> The interactions at different levels may be, and often will be, of different orders of magnitude. In a formal organization there will generally be more interaction, on the average, between two employees who are members of the same department than between two employees from different departments. In organic substances, intermolecular forces will generally be weaker than molecular forces, and molecular forces [will generally be weaker] than nuclear forces.

A completely decomposable system, then, is one in which the individual subsystems can be treated as independent from one another, but this clearly is not the case for product systems. Product components influence the behavior of the whole, just as the ideas and tastes of the culture can affect the purchasing habits and product usage of an individual. Nearly decomposable systems—in which interactions among subsystems are weaker, but not negligible—are thus a better approximation of complex product systems. Simon lays out two general properties of nearly decomposable systems: In a nearly decomposable system, the short term behavior of each level is approximately independent of the other component systems, while the long-run behavior is dependent upon the aggregate behavior of the other components [27]. The performance and behavior of a computer hard drive, for instance, can be viewed as

independent of the computer's other components: its performance depends on its internal components (platter, spindle, actuator, read-and-write heads, etc.), more than on other components within the computer (power supply, mother board, graphics card, or *their* internal components). However, the hard drive does not exist in isolation, and depends on and interacts with other components in an aggregate way. The hard drive is affected not by the specific movements of the computer mouse or the inner working of the processor, but rather by information and commands aggregated and sent to the hard drive over a standard interface connector and a standard power connector.

Figure 2.5: A hard drive's operation is relatively independent of the other components, save for aggregate information and instruction transmitted over a standard connector.

The property of near decomposability in complex product systems benefits designers, as it makes design a more manageable activity. Near decomposability allows the designer to understand, research, explore, and approach complex design problems without having to track every single part of the system closely and continuously. If it were necessary to address all aspects of a design at the same time, designing would be an impossible task. Instead, near decomposability allows designers to treat each part of the system as an approximately independent piece, thus providing greater focus and directing exploration in a limited and more predictable space.

At the same time, the phrase 'approximately independent' indicates that these chunks are not completely independent. Therefore every designer must be constantly aware of the ways in which design decisions impact, and are impacted by, other parts of the artifact system. The fact that systems are nearly decomposable allows designers to focus on the artifact or an individual component, despite all of the connections to other parts of the system, so long as there is

recognition of where and how these elements interface with the rest of the system. The successive division of a design problem (which can encompass social, artifact, and usage hierarchies) allows designers to attack each division in semi-isolation. This encourages designers to focus on a single element of the product system, recognizing that the complete design process occurs vertically and horizontally throughout the hierarchy, balancing efforts and decisions across all levels.

Near decomposability does more than just benefit the designer: it augments the adaptability and potential of the entire system as well. By reducing interdependencies across scales, nearly decomposable hierarchies allow each adaptive unit—whether designer, user, or manufacturer—to act independently, and better adapt the artifact and the system to meet their highly specific goals and needs within the context of use, without interfering with the other components [12]. This property allows parts of the system—the product, the use, or the organization—to change at speeds that are different than the rest of the system.

2.5.2 Layers of Change

The notion that the nearly decomposable layers of a system can change at different speeds holds significant value for the design process, as well as for the ways in which designed systems change and evolve over time. Famed ecologist C.S. Holling is one of the authors who popularized this notion by noting that the various levels of a hierarchical system have a tendency to move at different speeds. Holling's ideas will be discussed in much greater detail in *Chapter 4*; but for now what is important is that there are non-negligible interactions that exist between levels within complex systems. And as a result, individual layers adapt and change based upon other surrounding nearly decomposable layers. Each hierarchical layer of the system can influence, and be influenced by, the layers around it. Because of these interactions between layers, the behavior of the entire system is connected, and each semi-autonomous layer can both act to stabilize the layers around it, or to introduce change into the system [28].

Holling used a number of ecological and biological examples (forests, grasslands, the structure of an individual cell) to illustrate his point, but analogous behavior is also seen with designed artifact systems. One of the most thorough explorations of this phenomenon has been conducted in the realm of architectural design, with a focus on the *shearing layers of change* that

exist within a building. Originally coined by architect Frank Duffy, the shearing layers of change concept represents a building as a set of layered components which evolve over different time scales. According to Brand, Duffy stated, "Our basic argument is that there isn't any such thing as a building. A building properly conceived is several layers of longevity of built components." This idea was expanded upon by Stewart Brand in his book *How Buildings Learn,* in which he elaborates on the basic layers of change that can exist within a single building. All of Brand's "layers of change" can be seen in *Figure 2.6* [46]:

> **Site**—the geographical setting, the location, or the legally defined lot on which a building sits. Brand says that the "site is eternal," and implies that the site typically outlasts multiple generations of buildings. It is the most slowly changing level in the building's artifact system.
>
> **Structure**—the foundation, load-bearing elements, and support structure of a building. These elements are difficult and costly to change, and are therefore rarely altered; the structural life of a building ranges from thirty to three-hundred years, but most buildings don't make it past sixty.
>
> **Skin**—exterior surfaces like a building's roof, siding, windows, etc. These surfaces change roughly every twenty years, often in accordance with fashion or technology. They also facilitate repair and replacement, as they take the brunt of weather related building damage and degradation.
>
> **Services**—the working guts of the building: plumbing, electrical systems, communications wiring, heating, air conditioning, and other embedded systems such as elevators and fire prevention systems. These systems typically wear out or are rendered obsolete every seven to fifteen years, leading to their replacement—or in some cases, the replacement of the whole building.
>
> **Space plan**—the interior arrangement and layout of the building. The placement and location of walls, floors, ceilings, and doors. The space plan of most homes changes far more infrequently than that of commercial space, which can change as frequently as every three years. In both instances, the space plan allows occupants to bring the space into a closer alignment with their needs and desires.
>
> **Stuff**—all of the things which fill the building's interior space. The 'stuff' can change quite rapidly to suit the occupants' immediate desires and goals. Things like furniture, computers, appliances, light fixtures, and pictures can be shifted at a moment's notice.

Brand's concept of shearing layers is based on the work of ecologists like Holling and O'Neill [47] as well as biologists and systems theorists [48], but provides a powerful and relevant

insight into designed artifact systems. He notes that buildings are able to adapt and evolve over time because they allow for "slippage" between the various layers of change. The "stuff" in a building can change much more rapidly than the space plan or services; it is not obstructed by their slow pace of change. But each of these layers can change at a rate appropriate to its constraints and demands.

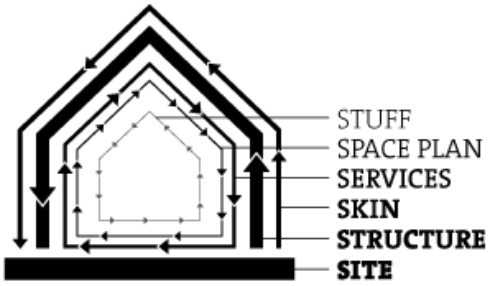


Figure 2.6: Brand's shearing layers of change as envisioned for architecture.

The shearing layers concept has since been co-opted by a number of authors in the realm of software, human computer interaction (HCI), and web design [49]–[51], but it is easy to envision a similar breakdown for physical products as well. For instance, in the complex artifact system that revolves around the personal computer—the 'computer eco-system,' if you will—there is a tendency for individual files and installed software to change quite rapidly. Users add and remove files, and do the same with installed software in an effort to maintain a set of information and capabilities that adequately meets their current goals and needs. Typically the installed software changes far more rapidly than the operating system itself, and the OS too can change at a different speed than the hardware on which it is run. Downloaded OS updates and full software upgrades can typically be installed without changing the computer's hardware, or the installed software programs. At the same, time individual hardware components can be interchanged and upgraded without affecting the components that exist at other levels of the system. In general, it can be said that core hardware (e.g. processor, motherboard, boot drive, etc.) changes more slowly than the installed hardware (e.g. RAM, disk drives, secondary drives, graphics processor, etc.), which change more slowly than the peripheral hardware (e.g. monitor, keyboard, speakers, mouse). It is worth noting that this ability to change at differing rates applies not only to the user's adaptation of the computer, but also to the design of each of these

pieces—the design of the OS does not change at the same rate as the design of the hardware component on which it resides.

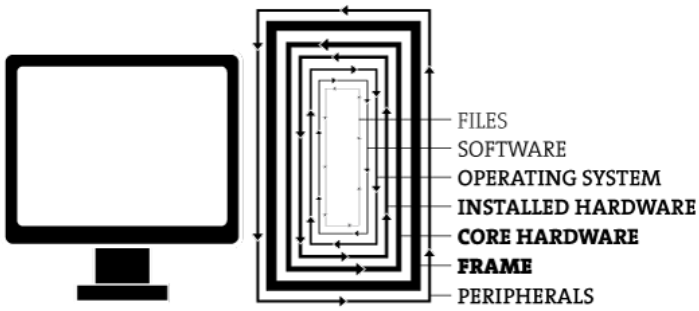


Figure 2.7: How the shearing layers diagram might be adapted for a computer; itself one artifact within a building's "stuff" layer.

However, each of these system components still influences and constrains the levels that surround it. Users frequently upgrade hardware components in order to achieve better performance for a newly installed software program—in order to run the latest graphically intensive computer game, users will frequently upgrade RAM and graphics processors, for instance. In order to power these more power intensive graphic cards, the user may also have to upgrade the computer's power supply or the motherboard in order to install additional RAM. There is also a symbiotic relationship that exists between the user's files and the hard drive on which it is stored. The desire to store more and larger files can lead a user to upgrade or install additional hard drives; just as additional storage space can allow the user to amass more and larger files. From a design perspective, installed software programs can incite changes in the design of the OS, and drive technology improvements in computer hardware—a desire for faster performance and increased capabilities within software has been one of the primary drivers of hardware technology. Conversely, the design of computer hardware can limit or push change in the OS and installed software due to changing capabilities and protocols.

Brand also looks at how stakeholders interact with the various levels [46]:

> The layering also defines how a building relates to people… The buildings interact with individuals at the level of stuff; with the tenant organization (or family) at the space plan level; with the landlord via the services (and slower levels) which must be maintained; with the public via the skin and entry; and with the whole community through city or county decisions about the footprint and volume of the structure

> and restrictions on the site. The community does not tell you where to put your desk or your bed; you do not tell the community where the building will go on the site.

Looking at how hierarchical products and product systems relate to individual stakeholders in the temporal domain is critical to understanding how products evolve and change in co-adaptive systems. In his book, *The Clock of the Long Now*, Brand looks at one representation of how these layers might function within the social hierarchy. Fashion and trends change more rapidly than commerce, which changes more rapidly than infrastructure, which changes more rapidly than governance, etc. [52]. While not adhering strictly to Brand's representation, it is possible to think of cases which illustrate the layers of change in the social hierarchy of a complex product system.

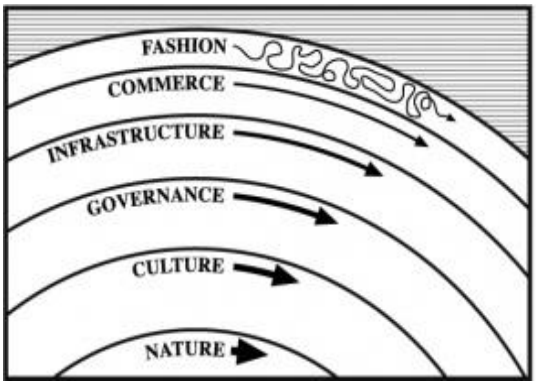


Figure 2.8: Brand's shearing layers of change as envisioned for the larger social hierarchy.

Products typically change more rapidly than the companies that design them, and the culture in which they are used. When Apple originally released the Newton, they identified a possible need for portable personal computing that would eventually become a gigantic market (PDAs and smart phones). While there were certainly flaws with the device itself, it is also likely that the surrounding technological infrastructure (or lack thereof) and the culture into which the Newton was released played a role in the Newton's failure. Individuals' expectations and desires (as well as the surrounding technology infrastructure) were not yet aligned with the capabilities

that the Newton provided. In this way, the surrounding culture can be viewed as one factor which constrained the artifact system.

At the same time, products are capable of driving change within cultures. Years later, Apple would release the wildly successful iPod MP3 player [53]. The runaway success of the iPod and its bundled music distribution and management software, iTunes, changed the culture that it was embedded in—fundamentally altering the way people purchase and listen to music, and, some would argue, the way individuals interact with one another in public [8]. The iPod's influence did not stop there. Following the success of the iPod, Apple shifted away from primarily being a computer manufacturer, in favor of becoming a manufacturer of personal electronics—most obviously evidenced by Apple Computers dropping 'computers' from its name. Apple would go on to design and manufacture the hugely successful iPhone and iPad, which likely would not have been possible without the iPod.

Looking at these and countless other examples, it becomes clear that these hierarchical properties are inherent in every artifact system. The complete hierarchy of any artifact system spans the artifact's internal structure and the larger human systems in which it is embedded. Changes to a computer's CPU *can* result in changes in system levels as far removed as culture and commerce. This means that designers must attempt to maintain an understanding of not only the product, and not only the components, but also the higher hierarchical levels in which the product is embedded. Maintaining a detailed and accurate understanding of the entire product system, however, is simply not possible. Thankfully, as the result of the previously illustrated property of near decomposability, designers are able to isolate portions of the system in order to make the design process more manageable, and design problems more tractable. Near decomposability is the property of hierarchical systems that allows designers to break designs up into individual chunks that serve specific purposes [54], [55]—whether those chunks are individual sub-assemblies, the entire product, or the interaction of the product and the user is only a matter of perspective and how designers choose to break up the system in order to facilitate design activity.

As designers focus on individual chunks of a design, there is a natural tendency for designers to focus on a specific level, and the level immediately above [17], as those are the interactions of the most immediate concern to the designer. It is typical to focus on a sub-assembly and the assembly into which it fits, or the assembly and the way it interacts at the level

of the artifact. While this ensures that closely related systems and hierarchical levels will mesh, this type of decomposition often leads designers to neglect the interdependencies that exist across larger scales and systems. Viewing a product in this way can predispose organizations to overlook important interdependencies that exist between less obviously connected system components. An intense focus on the artifact frequently leads to an imprecise understanding of the interactions between the artifact and its surrounding systems—usage, production, maintenance, culture, etc.

These interconnections can lead to emergent behavior at any level of the system, resulting in unanticipated behaviors and breakdowns. A good example of a large-scale design failure that occurred as the result of considering only a few hierarchical scales was the United Kingdom's ambitious ID card program. In 2006, Parliament established the Identity Cards Act intended to provide identity cards linked to the National Identity Register database. The act itself was decried and debated by all manner of activists, technology experts, and politicians. But apart from the controversy, the ID cards themselves serve as an example of all that can go wrong when designers fail to consider multiple levels within a product system. Run by the Identity and Passport Service (IPS), the intention of the £4.7 billion ID carding program was to provide law enforcement agencies with information in order to prevent counterfeiting, fight terrorism, and increase security at borders [56].

Figure 2.9: Putting aside any political or social debate, the implementation of the UK ID card saw a number of problems emerge as the result of failures to consider the influence of other hierarchical levels.

The ID itself was quite impressive. It contained biographical and biometric data including facial and fingerprint scans, and it served as one of the first digital travel documents. But when viewed in light of the larger system, there were a number of unanticipated behaviors.

First and foremost, the government neglected to purchase the card readers necessary to extract any of the additional biometric data—essentially rendering the cards very expensive photo IDs. Further, the government made no plans to introduce the readers; a member of the IPS stated, "there's no prospect in the immediate future for the government directing anybody that you have to buy those things [readers], because we would be placing a burden on these organizations…. The manufacturers of the machines [readers] have also got to decide whether it is worth their while to produce them" [57]. It seems almost unbelievable that the Parliament would neglect to plan for the implementation of card readers, or ensure that manufacturers were on board prior to rolling out the card program. Eventually, all of the cards were invalidated when the Identity Cards Act was repealed in 2011 [58]. Although political and social agendas were contributing factors to its repeal, the design and development of the UK Identity Card program saw a number of problems emerge as the result of failures to recognize the impact of other hierarchical levels.

Accordingly, many authors have recognized the importance of "…analyzing complex objects at all levels" [16], [59], [60]. While hierarchy and near decomposability provide a structure through which designers can understand and manage the complex interactions inherent in product systems, it is important to recognize and understand the cross-scale interactions that occur. Every level is a subsystem of the whole: the various levels embodied within the artifact, the artifact itself, the users, and the surrounding culture all affect the behavior of the product system. Accordingly, no system can be understood, or designed for, by examining only one scale or level [39].

Therefore, it is necessary to dynamically alter the way in which we define our system of interest. In breaking up a nearly decomposable system, we are essentially drawing boundaries in order to keep the complex product system understandable and manageable [16], but as these systems are nearly decomposable, rather than completely decomposable, we are still breaking some interconnections and interdependencies. It is necessary to re-define the boundaries of the system on which we will focus, and view it from multiple perspectives. Drawing the boundary around the user or the artifact in order to make the design problem tractable is necessary and acceptable, so long as we simultaneously view the product in conjunction with its larger context and culture.

2.6 Perspective and Bounded Rationality

Designers are primarily concerned with the specification and production of artifacts to be used by others within contexts very different from their own. The ultimate goal of the designer is to support individuals' goals and needs in their context of activity, with the intention of supporting tasks at the level at which they become meaningful to the stakeholders who engage in them [15]. In this way, design is tightly coupled to the concept of *perspective*: designers must understand that they are designing *from* their own perspective, but *for* the perspectives of others. Many design approaches—from user-centered design to participatory design—are all about acquiring, understanding, or contributing to the user's perspective.

At the same time, designers must recognize that regardless of the specific methodologies used, one cannot approach a design problem from an entirely neutral perspective. Every question and every idea grows out of what Winograd and Flores refer to as a "pre-understanding that opens the space of possible answers." Designers are pre-disposed to certain ways of thinking, defining problems, and understanding as a result of their own education and experience, and the culture in which they live and work—the designers "way of being" [17]. This internal predisposition is typically not as obvious as a process or method, but it still colors the way in which the designer thinks and approaches a design. It shapes the space in which designers define problems and search for solutions, as well as the way in which they evaluate those problem settings and solutions.

As a result, would–be designers are predisposed to a version of the classic psychologist's fallacy. The psychologist's fallacy, loosely defined in the context of design, is when a designer assumes that their distant understanding of the user's activities and context is correct—that it captures the actual experience of the user and their context in an intricate and accurate way. In this way, the designer's perspective, even informed by methodologies and approaches geared to account for other perspectives, "…blinds the designer from seeing how users are currently adapted, as well as how they may adapt to a new artifact" [61]. This brings to light two relevant points about the designer's perspective: it not only limits their understanding of a user's perspective, goals, desires, and responsibilities; but, in turn, it also limits their own ability to envision how users will respond to, adopt, understand, and apply new designs.

A designer's perspective, then, limits understanding and anticipation, potentially leading to designs that do not fit with goals and needs within the actual—rather than perceived—field of activity. Beyond that, perspective influences the way in which designers view problems and define potential solutions. It can often lock designers into previous ways of thinking [62], design tracks [63], or problem settings [64], rather than encouraging new framings [65] of the problem or explorations of new meaning [66]—which are often the key to innovation.

This ultimately leads to designers making decisions that fit within their own perspective, despite being less than ideal vis–a–vis other agents within the product system. Designers operate in a finite world, acting on limited information because there is never enough time to *fully* understand any problem, user, or context. Simon called this idea *bounded rationality*, saying "…as creatures of bounded rationality, incapable of dealing with the world in all of its complexity, we form a simplified picture of the world, viewing it from our particular vantage point and our particular interests and goals." [38]. Because of the complexity of artifact systems, designers are forced to simplify the world for which they design. This process of simplification is founded upon the designer's perspective and goals, and the ways in which that simplification is achieved vary accordingly.

As a result of limited perspective and bounded rationality, designers *satisfice*; that is, they make the best decisions they can, based upon the information that they have immediately available to them [12], [38]. In the face of incomplete perspectives, partial understanding, and a limited ability to anticipate, designers use the tools at their disposal in order to design the best artifacts that they can, creating products that they feel best approximate the current state of the world and their understanding of how that world might change in the future. Of course, designers can never fully know how the world will change—particularly with respect to the introduction of a new design, and how users will react to, or apply, their designs in the field of practice.

Despite those difficulties, it is possible for designers to take steps to both recognize and overcome their own perspectives. Many current design approaches are a first step, but it is never possible for designers to ever be fully rid of their perspective and inherent biases. Designers then must make themselves aware of the effects of their perspective on their understanding of the current world, their predictions of the future world, their approaches to developing design solutions, and their focus within the problem space. By becoming aware of our prejudices, we

can free ourselves from many of the limits they place on our thinking [17], and better see the interactions and interdependencies that are relevant from other perspectives. As humans, we have the ability to view both the components of the system and the relationships between components from a variety of differing perspectives—each of which "simultaneously reveals and obscures" [60].

2.6.1 Artifacts as Hypotheses

For the reasons discussed above, the behaviors of complex systems are impossible to fully predict. In product systems, this is due in large part to the bounded rationality and limited perspective of designers. But the difficulty in predicting the behavior of product systems goes beyond a lack of understanding; it relates to the inability of design organizations to anticipate change. Behavior patterns emerge as a designed system plays out over the course of time. These emergent behaviors affect everything about the *actual ways* in which designs perform, designers design and learn, and users adapt designs to fit their contexts and purposes.

The way in which a designer represents and understands a system is a matter of perspective and purpose [61]. As a result there is no single correct perspective on the system, nor is there a way to determine a single "best" perspective [17]—every representation of the system is an imperfect interpretation. Combine that idea with the complexity within product systems, and it leads to a situation where it is impossible to accurately predict the results of our actions. Designers cannot perceive all of the ways in which a product will affect or restructure the surrounding environment, the task context, or a user's goals and desires.

This unpredictability and change is partially due to a lack of perspective, but it is compounded by the problem of envisioning designs for situations that are both *spatially* and *temporally distant* [55]. Spatially distant means that designers are designing for a context and environment which is not their own—largely the previously discussed problem of perspective. Temporal distance refers to the fact that designers are envisioning products for *future* contexts and situations of use, which do not yet exist [67]. Designers typically are attempting to anticipate and construct designs for these two situations simultaneously, which often leads to designers being uncertain as to the effects of their designs.

Once a design reaches the market, it never perfectly conforms to the user's needs; users are forced to *satisfice*, adapting the design and their activities to meet their specific demands [7], [18]. The result of the introduction of a new product is the transformation and adaptation of the artifact and the system, with new designs altering the tasks and situations for which they will be used [15]. Because of this, designers can never be completely certain about how a design will be used, applied, or adapted in actual practice. Products themselves can never be more than the physical instantiation of a designer's hypotheses, or theories, about how users' goals, activities, and contexts will be transformed by the design [15], [17], [68]. In essence, it is never possible to fully anticipate how a product will be used, and as a result designs embody decisions made by designers in the face of uncertainty.

This situation puts a focus on learning and treating designs as experiments rather than once-and-for-all statements about what is useful in a field of practice [17], [68], which leads to questions about what designs can teach us about user's desires, understandings, and the contexts of use. In order to learn from previous designs, and the adaptations they trigger, we are pushed back to the issue of perspective. Designers and organizations must begin to capture the information that is only present at the sharp-end of the system—at the intersection of the product, the user, and the context [12], [69] in order to design artifacts that are capable of adapting in the face of certain change.

2.6.2 Local-Global Trade-offs

The limited perspective of designers, combined with inherently finite resources, leads to bounded rationality. As a result, designers satisfice by leveraging the information and resources that are available to them. This results in locally rational behavior in which designers make the best decisions possible from their perspective, based upon information accessible to their position within the larger system. Accordingly, decisions such as what the design's capabilities should be, how the design should be used, or what it should afford are likely to be *locally adaptive*—meaning that they best balance the constraints and trade-offs based upon the information available to the designers. At the same time, the possibility exists that these decisions will be less than ideal when viewed from other perspectives within the system (users, manufacturing, clients, etc.), as these stakeholders attempt to apply the design in their own

unique context. In this way the designers' actions are *locally adapted* to their knowledge and purposes, but *globally under-adapted*, in the sense that they are less than ideal with respect to the other stakeholders' goals and needs. Thus the potential exists for designers to work at cross-purposes from other stakeholders, with designers pursuing their local goals at the expense of the users' experiences or needs. In this case, designers' decisions can be seen as locally adaptive and globally maladaptive, in the sense that they actually degrade the performance of the entire product system [70].

Globally maladaptive behavior frequently happens when designers seek to reduce costs, or employ new technologies, without considering the effect their decisions will have on end-users. Conversely, it can also arise when designers prioritize the end user, with new design features and capabilities that negatively impact manufacturing by requiring expensive, difficult, or untested manufacturing processes. One might assume that this sort of behavior doesn't happen very often, but examples of locally adaptive, globally maladaptive behavior are everywhere. One probably does not even have to look very far in order to find an example; in fact, one may only have to open their refrigerator.

Since 2007, Wal-Mart, Sam's Club, Costco, and other large retailers have begun selling a redesigned milk jug that drastically improves shipping and cooler utilization [71]. The new jug is rectangular in shape, and can be stacked and packed much more efficiently than traditional milk containers. The new jug results in 180% higher utilization of coolers, 125% better pack efficiency, and even reduces the cost to the users by 16%. As a result of the redesign, however, customers have struggled to effectively use it to pour milk, resulting—quite literally—in higher incidences of spilt milk. As this was not an issue with the previous design, negative reaction from consumers has been strong. So strong, in fact, that there have been a number of publications decrying the new milk jug [72]–[75]. Complaints have been so prevalent that one company has begun selling a reusable cap with a built in spout intended to fix these problems and "…allow you to pour milk again!" [76]. In this instance designers clearly became trapped in their own perspectives motivated by efficiency and cost.

Figure 2.10: Square milk jugs offer many advantages, but ease of use is not one of them. This resulted in a second product intended to fix issues which could have been better addressed in the original design.

Even user-centered design and usability testing open the possibility for globally under- or mal-adapted designs: this behavior can also be seen in many artifacts that have been designed using these approaches. One group of interdisciplinary designers recounts their experiences accordingly [77]:

> Some years ago we made usability tests of an existing product for a particular product line. A number of problematic aspects of the design was identified and reported to the engineering team. A year later the engineering team returned with a new design, which we once again tested with invited users. The result was discouraging. Although all the originally identified problems had been dealt with, the new product had as many flaws as the old. We were puzzled by this incident, not because it was hard to understand what had happened, but because it questioned the contribution that we could bring to product development.

Because user-centered design is focused on addressing very specific problems related to use and usability [19]—rather than pursuing new problems—there is a tendency to use usability testing to ensure that a design is locally optimal, in that the usability of a particular feature is sufficient. However, the particular problem under study may not be relevant to users, or address their actual needs with regard to how the design will perform in their lives. Optimizing the details of a given design solution, rather than searching for the best version of the design can be seen as globally under-adapted behavior that arises from failing to escape our own perspective [78]. Essentially, designers can end up developing a good solution to the wrong problem [7].

2.6.3 Acute-Chronic Trade-offs

Acute-chronic trade-offs are another type of trade-off frequently present in complex artifact systems. These trade-offs are most typically evident in conflicts between short-term and long-term goals. Short-term goals can generally be assessed through data collection and offer immediate results. In product design, these short term goals can vary from raising profits to increasing usability—or in the case of the milk jug improving throughput, pack densities, and reducing cost. Conversely, long-term, or chronic goals, are generally harder to prioritize and achieve as they are dependent upon the interaction of the system's component parts over time [44]. In product systems, these are factors such as long-term profitability or a corporate strategy for innovation. Innovation requires extra investment, research, and exploration—or at the very least, the accrual of additional risk—in order to identify and pursue alternative directions [79]. Incremental improvement, on the other hand, can be achieved much more quickly and safely (at least in the short-term) by quickly building upon what has already been done. Essentially, this leads to a tension between short-term goals (shipping products more quickly at increasing margins), and long-term goals (pursuing innovation, quality, safety, or long-term organizational success).

Returning to the discussion of user-centered design, Brand points out that the while user-centered design puts the user's perspective first, it does so in the most *immediate* sense possible. It focuses intently on the *acute* and *current* needs by honing in on a very *specific* set of features, which have resulted from problems directly observed in user research and usability studies. He argues that the problem with user-centered design methodologies is that they pursue designs that are all too optimized to the present situation and context, and largely ignore potential innovations, adaptations, and future users. User-centered design prioritizes the acute over the chronic, making its solutions less adaptable to unknown future conditions, new contexts, and competitive markets [46].

Combining user-centered design's acute focus with its tendency to be locally adaptive, sets the stage for *creeping featurism*. Creeping featurism occurs when products are overwhelmed by "inadvertent cumulative complexity" in which new features—useful in their own right—are continually added to a product, to the point where the overall increase of features leads to complexity which severely limits usability [63]. User-centered design has the tendency to follow

"…standard prescriptive approaches to technology development by solving short-term small repair problems at a local scale…" [80]. By pursuing these short-term problems at a very local scale, usability testing promotes a highly iterative design process in which designers struggle to do anything more than continually fix small problems. While these methodologies are very effective at identifying and addressing these locally defined issues, they frequently fail to explore new directions, identify emerging aspects of the problem, or revaluate previous design features and decisions. Feature creep, resulting from traditional user-centered design methodologies, is a persistent example of designers—despite their best intentions—prioritizing acute goals, ultimately leading to drastically reduced usability and the chronic failure of a design.

This behavior leaves designers trapped in a singular design direction, incapable of escaping continual improvement and the continual addition of features. New features, in and of themselves, can often be seen as adaptive behavior, but when viewed across longer time scales or from the perspective of the whole product system, often turn out to be globally mal-adaptive. "Designers add new features to existing designs, and usability engineers test and fix usability problems through evaluation." [78] Each new feature, viewed in isolation, can be judged to be well designed and usable, but when all of the features are integrated into a single product each increases complexity and complicates use.

Creeping featurism can be seen as a symptom of complex artifact systems. It emerges from the behavior of interacting system elements, as the product's reduced usability only becomes evident as the result of the interaction of multiple features, each designed to serve a different purpose. Creeping featurism shows up frequently in all manner of products, from computer software to cell phones. Television remote controls are a particularly good example of this phenomenon: as home entertainment systems have grown, so too has the number of devices that need to be controlled. As a result, universal remote controls have added modes and features in order to provide the user with one remote that can perform the functions of several controls that came with receivers, DVD players, VCRs, TVs, cable boxes, etc. Inevitably this leads to remote controls that are flush with buttons and modes but that are largely unusable. Each button certainly does the job it was designed for, but the complexity of the remote has skyrocketed, as managing five or more devices with a single remote is next to impossible. As a result, users are frequently left to struggle to perform the few actions that they actually care about.

In fact, investigating one particularly problematic television remote (*Figure 2.11*) reveals a control that has forty-nine buttons in addition to those found on a 'standard' remote control (ten numerical buttons, channel up and down, volume, and power)—it actually has sixty-four buttons, if those are counted. The difficulty of interaction resulting from this feature creep is not solely the result of the sheer number of buttons or the user's inability to find the appropriate button. Many of the problems are a result of the increasingly complex interactions and functions necessary in order to control multiple devices, embodying multiple sets of different features and capabilities. This particular remote has two 'mode' buttons, a 'shift' button, four buttons labeled with the letters 'A', 'B', 'C', and 'D', and two buttons with no labels at all (just round black buttons with no apparent functionality). After years of use, many users may still have no idea how to take advantage of the majority of this remote's capabilities; instead many users revert to relying on a set of other more dedicated remotes to control a suite of devices (TV, DVD player, cable box, etc.).

In his book *Designing Interactions*, IDEO co-founder Bill Moggridge presents a humorous solution to the feature creep associated with television remote controls (seen below) [81]. This "prototype" is presented largely in jest, but can be seen as a satire, of sorts, in that it ridicules the design with the intent of encouraging improvement. The design of remote controls has not come to this point by chance. It is a result of design organizations prioritizing individual features, short-term goals, and narrowly defined usability within the design process. It is a result of designers ineffectively balancing acute-chronic and local-global trade-offs within a complex system of devices, uses, and human performance.

Figure 2.11: One of many problematic universal remote controls, and a "prototype" of an improved design.

Designers must recognize that these acute-chronic trade-offs extend well beyond user-centered design and usability. They are pervasive within the design process, the discipline itself, and even human nature. It is easy to give preference to the acute problems: the more immediate the problem, the more likely it is to be the beneficiary of attention and efforts. These matters are invariably more pressing than longer term problems and goals—the "squeaky wheel gets the grease." But by their very nature, these decisions are trade-offs. In focusing on the acute, attention and resources are diverted from the chronic. While this may frequently work to the benefit of the design process, it leaves the design more susceptible to unexpected changes in use or market conditions. In fact, combining these trade-offs with designers' limited perspective and bounded rationality guarantees the emergence of new uses, misuses, failures, and adaptations within the actual product system. There is no omniscient perspective and trade-offs are inherent; as a result, emergent behavior and surprise will always be a part of any designed system.

2.7 Emergence, Change, and Adaptation

There is no such thing as a complete perspective on a complex product system. When combined with the interdependencies that make up the system and its structure, behaviors emerge from the system that designers cannot plan for or anticipate. These emergent behaviors will always be a part of product systems—even the best designers and the most highly structured designs are subject to surprise when they collide with the "real world" of users and contextual

factors. The effects of this surprise, however, are far reaching, and go well beyond a few unexpected behaviors of the artifact. New uses and users emerge, but the introduction of a design into an ongoing field of activity has the potential to incite substantial and meaningful change in all parts of the system. The introduction of an artifact can lead to changes in uses and users as well as organizations, economic systems, and cultures. In this way, products have the potential to act as agents of change that have the power to deeply alter the user—goals, desires, capabilities, etc.—as well as the context of use—the environment, activity, or interactions between agents. It is not simply that products are unpredictable in terms of their success and failure, but rather that they have the power to alter everything about the product system and change the course of an activity, a culture, or a society.

A humorous, but telling, example of this unpredictability can be found in George Basalla's classic book, *The Evolution of Technology*. One of the first, and most well-known, authors to study the evolution of artifacts and products, Basalla would seem to be uniquely positioned to anticipate the performance and effects of new technologies. But in 1988, when speaking about the personal computer he said this [82]:

> By the mid-1980s the home computer boom appeared to be nothing more than a short-lived and, for some computer manufacturers, expensive fad. Consumers who were expected to use these machines to maintain their financial records, educate their children, and plan for the family's future ended up playing electronic games on them, an activity that soon lost its novelty, pleasure, and excitement. As a result the device that was initially heralded as the forerunner of new technological era was a spectacular failure that threatened to bankrupt the firms that invested billions of dollars in its development.

What a stunning miss! Even one of the most frequently cited commentators on technology change could not predict, or recognize the eventual value of the personal computer. Not only was the personal computer not a fad, but it would go on to completely transform American society and the world. Organizations adapted the way in which they worked and conducted business activities, and the connectivity they provided—initially through email—changed the way individuals communicated with one another. The internet, which could only emerge in its current form as the result of computers, would eventually put a world of information at our fingertips. Computers would go on to infiltrate our businesses, homes, and every aspect of our lives—from shopping and banking to driving and entertainment. Eventually,

designers and engineers—coupled with the evolution of technology—would put the power of the "personal computer" into our pockets with smart phones and other internet enabled devices, further enabling new behaviors and changed interactions. Each of these technological innovations could only emerge as the result of the introduction of the personal computer, and none could be envisioned at the time of its introduction.

2.7.1 Surprise, Adaptation, and Transformation

As designers, we must realize that the introduction of a new artifact into a field of activity has the ability change everything about the surrounding system—and the artifact system can, in turn, initiate changes in other systems that interact with it. Put simply, artifacts have the power to initiate "cycles of transformation and adaptation" [15], [17], [68]. Artifacts can, through their presence in a system, introduce new complexities and capabilities, which have the potential to change the user's, or the artifact's, role within a particular context. This added complexity allows users to adapt in the pursuit of their goals, and even adapt the goals themselves [83]. These adaptations and transformations can be massive and transformational, as in the case of the personal computer outlined above, but they routinely occur in much more nuanced ways as well. In fact, almost all products incite some manner of transformation and change in the systems to which they belong, with the artifact changing the user's capabilities, expectations, or the tasks and activities in which they engage.

This adaptation and transformation is frequently unpredictable, and occurs as the result of the intersection of three previously discussed factors that are inherent to complex product systems: First, the large number of interactions and interdependencies spread throughout the product system create interactional complexity. Secondly, the adaptive agents within the system (primarily users and designers, but many more) shift their behavior as a result of the artifact and the context; these agents have goals and adapt in order to meet those goals. And finally, limited perspective and bounded rationality mean that no designer or user has a picture of the whole system—designers possess information that is not available to users, just as users have information about their local context and field of activity that are not available to designers [84]. As a result, agents frequently behave in ways that are locally adaptive, but globally under- or mal-adapted.

The interaction of these factors gives rise to product systems that behave in inherently surprising ways, as new artifacts lead to a chain of adaptations. Consequently, designers and design organizations are frequently surprised by the behaviors of their artifact systems: the ways in which a product succeeds or fails, the tasks for which it is used, the new desires it incites in users, the contexts in which it is used or adapted for, and the users who actually purchase it are all frequent areas in which the design's actual performance does not match what is expected by the design organization. The Honda Element is one example of a product whose behavior in the market was surprising to the organization responsible for its design and implementation. While the vehicle proved to be relatively successful, Honda was reportedly surprised by how and, more specifically, *who* purchased and used their vehicle.

Figure 2.12: The Honda element was designed and marketed for active 'Gen-Xers' who liked to surf and camp, but ultimately found value for a very different market and set of activities.

Introduced in 2003, the Element is a boxy and utilitarian vehicle that was, according to Honda, designed for college-aged men, who frequently participated in outdoor activities. Internally, Honda referred to the vehicle as a "dorm room on wheels," and it was initially marketed as a vehicle that could haul surfboards and mountain bikes, be slept in, and be hosed out for easy clean up [85]. The designers' intent can be seen in a number of the Element's features that were stressed in a series of hip commercials geared toward a young consumer: 64 seating configurations, water resistant utility floor and seats, and a removable center console cooler. The same demographic and uses were also stressed in the earliest vehicle reviews. *Car and Driver* magazine positioned the Element as a vehicle that was specifically targeted to the "…young and active psychographic/ demographic…," that was "…conceived and designed

specifically to attract 22-year-old men with 'many friends' and a lifestyle so active you and I would need amphetamines just to keep up." In that same article, *Car and Driver* continues [86]:

> [The Element] offers Mr. X Games so many seating, sleeping, and cargo options that he won't know what to do with himself. He could actually move out of his parents' pad and just go mobile. For starters, the pillarless side doors open wide—78 degrees for the fronts, a full 90 degrees for the rears—creating a huge opening for 'side-gate parties' or loading big gear… Since our young gun is so popular and active, he can transport himself and three friends, plus 25 cubic feet of gear; or he can bring along one buddy and cram in more than 70 cubic feet of detritus, or two mountain bikes, both of which will fit between the rear seats that recline and fold flat against the sidewalls; or if he and his pal want to fit five more cubes of stuff, they just take out the rear seats entirely, which requires strong arms, a healthy back, and the removal of two trim pieces from the sidewalls…
>
> A little shut-eye? No prob. The floor is totally flat, and with the rear seats up or removed, one or two six-footers can crash for the night. Honda says two people could catch zees lying on the front and rear seats — they recline "flat" to form a lumpy bed — but only if they're used to sleeping on Nerf footballs. And did we mention that the seats are waterproof and the urethane-coated flooring beer-proof, Taco Bell-proof, and hurl-proof?

The *Car and Driver* review concludes by referencing the Element's low price point and stating that, "with prices like that, it's hard to imagine Honda dealers having a hard time selling such a unique, versatile, fun-to-drive vehicle. But the Element's target demographic is a fickle, picky, image-conscious group, so you never know. Still, we think Honda's got a good shot at moving the 50,000 units it hopes to sell in 2003." In its first year, the Element sales exceeded this target; selling 67,478 units [87]. Those sales, however, did not come from the market segment that Honda explicitly targeted.

Honda designed and advertised the Element for Generation-X and Generation-Y, and hoped to get parents to buy it for their kids. But the Element never made it to the youth market. Instead, "…the parents who bought it decided they wanted it. The whole car got hijacked by the baby boomers." Middle aged drivers who have never used the rear-seat sunroof—designed for transporting surfboards—have found the adaptable space of the Element perfect for antiquing, transporting pets, remodeling, and hauling materials for work; and they appreciate the easy to clean interior not for hosing mud off of mountain biking gear, but for easily cleaning up the cumulative mess from breakfasts and lunches on the go…" [85]. In 2009, six years after the

Element's initial release, the average age of an Element owner was 49 years old [88]—a far cry from what its designers envisioned, in terms of both demographics and use. But this was not necessarily a negative surprise, or a failure, as Honda—and other manufacturers like Kia and Scion, who have since jumped into the youth-oriented boxy cars for baby boomers market—are no doubt happy to manufacture the vehicles for anyone who wants to purchase them.

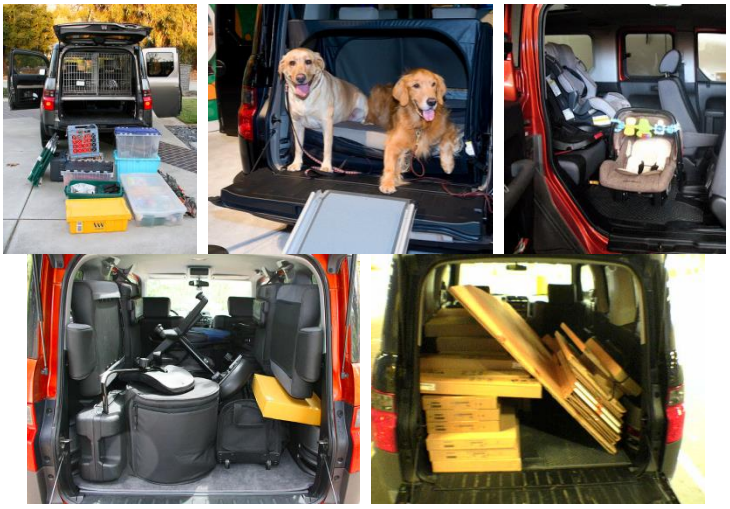


Figure 2.13: The functionality and hauling capabilities the Element afforded to "baby boomers" are very different from what designers had originally intended.

Beyond simply opening up new markets and demographics, designed artifacts have the power to transform the way in which people engage in tasks, what tasks they can perform, as well as what they try to accomplish [80]. The structure and design of an object is critical to determining the ways in which users interact with it, as well as the ways in which they adapt to the new capabilities and opportunities that the product affords [89]. In this way, designs also have the power to shape a user's expectations, cognition [7], and the lens through which they view all other artifacts—those that currently exist and those that are yet to be designed.

While the example of the Honda Element may seem trivial at first glance (a mere example of misinformed designers and marketing executives), if one looks deeper, it is possible to see the ways in which it transformed the goals and capabilities of its middle-aged drivers. The Element provided drivers with a large, practical, transformable, and adaptable space that fit their lifestyles, regardless of what that lifestyle actually was. Rather than just being well designed, these

features allowed the drivers of the Element to take on new tasks that they were unable to perform with a traditional sedan. It allowed them to transport large items for work and home, or to quickly clean out the back after carting around a new dog. Ultimately, it was this adaptability, in combination with the new capabilities it afforded to its drivers, that was the primary reason for the success of these "boxy" vehicles. The Element was ultimately discontinued in 2011, but throughout its life the design persisted relatively unchanged [88].

In many ways, the Element can be seen as an example of a product that unexpectedly opened new opportunities, which were then exploited by users to expand their capabilities, thereby developing new aspirations and goals. It is an example of a more general pattern of complex adaptive systems, which Woods and Hollnagel refer to as the *Law of Stretched Systems* [61]. Applied to the context of artifact design, the "Law" states that as new features, products, and capabilities are introduced into the user's field of activity, they are quickly exploited, leading to a changed interaction with the product and the activity. The introduction of a new product changes how users interact with a design, the activities they *can* perform, the activities they *want* to perform, and even their needs, dreams, and expectations. As stakeholders develop new goals and purposes, these changes lead to new demands on the current artifact and new constraints for future artifacts.

For designers, it is not possible to address a need or design problem *completely*, as the act of addressing past issues simply opens up new goals, desires, and challenges that must now be dealt with, and past successes lead to future demands [60]. This is a critical component in the nature of adaptive product systems, as successful designs push future demands. These new demands inevitably lead to new designs as they make the current system less ideal, and hence more likely to fail or be displaced by another design. This idea is at the core of what drives design and technology to evolve over time: organizations design artifacts to meet the needs of today. Once in the context of use, the design itself provides capabilities that lead to new desires and expanded goals (which cannot be anticipated prior to the product's introduction) that often call for new designs. Embedded in complex systems, successfully designed artifacts almost ensure their own downfall by changing the way users perceive the world and their own intentions—calling for more or expanded functionality and ultimately their own replacement.

This is indicative of a larger pattern, and a third type of trade-off, within complex product systems: the *optimality-brittleness trade-off*. In essence, as a design becomes better at meeting

some set of challenges, it inevitably become more brittle with respect to others. Attempts to improve the performance of a product along some dimensions inherently increase its likelihood of failure when it encounters other contexts or demands [70], [90], [91]. The optimality-brittleness trade-off is frequently visible in light of failure. For example, one can look at a company like Kodak, or a product such as the iOmega Zip Disk, as a system element that was optimal for a particular context or set of constraints, only to be ruined as the result of a changed environment. Both achieved a great deal of success, but were rendered worthless when the context around it changed—the onset of digital cameras and optical disk drives, respectively. Neither designs nor companies can be well positioned for every possible future. Progress in one direction leads to fragility in another; a focus on one set of constraints or one part of the design problem necessitates that other constraints or problems are ignored as the result of finite resources.

The combination of the optimality-brittleness trade-off and product systems 'stretching,' in order to achieve new levels of productivity and capability, leads to new goals and challenges that that make the current design solution more brittle and less likely to adequately fulfill its purpose. This results in cycles of adaptation and change, as designers and users respond to the changing state of the system—leading to further adaptations and changes. New products change users' capabilities and expectations, which drive future design processes and the functionality of future products. Once released, these products cause users to again adapt their behavior and goals, reducing the appropriateness of the design. This cycle pushes ever forward, and drives technology change. But within product systems, design organizations are not the only source of adaptation, as users also have the ability to adapt physical artifacts in order to better address their changing goals and expectations. When an artifact can no longer accomplish all of their goals users frequently tweak products, adapt designs, and develop work-arounds that allow them to meet current goals with their current products. These adaptations can take the form of changed behaviors, strategies, or processes, or they can lead to the actual adaptation of the artifact by the user. Each of these, however, is done in order to extend the user's ability to meet needs and goals within their changing field of activity [69].

In order to keep pace with the system changing around them, users frequently alter their behaviors and their products. These behaviors are everywhere within the designed world, and can be seen in a home-owner sticking a shim under a table leg so that it better matches the

physical space (and quits wobbling!), or an operator attaching post-it notes to an industrial robot as a reminder of how to operate a device. These changes can be relatively 'small fixes,' but user adaptation often transcends small problems in order to powerfully transform the capabilities and applications of an existing product. By adapting existing designs users, rather than designers, can influence the direction of the product system by exploring new functionality and applying their own creativity and problem solving skills. One recent example of this is hospital surgeons adapting the Microsoft Kinect gaming peripheral into a useful surgical tool. Originally designed as an input device for video games, surgeons have adapted the product to improve surgical procedures, reduce the risk of contamination, and shorten the length of the surgery.

Figure 2.14: The Microsoft Kinect, was developed for gaming, but has since been adapted for a number of other purposes.

The Microsoft Kinect is a motion sensing input device first developed for the Xbox 360 gaming console, which allows individuals to interact with the console without the use of a controller. The Kinect uses three depth sensors, an RGB camera, and multi-array microphone in order to track the movements of a player in three-dimensional space. Through moving their bodies, performing gestures, and using voice commands the user can interact with the console to control video games and other supported software. Following its release, doctors at Sunnybrook hospital in Toronto transformed the Kinect into a critical part of their surgical procedure. The surgeons use the hands-free motion controller in the operating room to interact with MRI scans through hand gestures. This allows doctors to manipulate and view MRIs to gain information critical to the surgery without ever having to leave the sterile environment. This is a far more hygienic and streamlined approach than the previous method, which could take as much as twenty minutes for the doctor to leave the sterile area, view the MRI scans on a PC, and then wash up before returning to the patient [92].

Figure 2.15: The Microsoft Kinect gaming peripheral as adapted for the O.R.; a context far removed from its design intent.

Since its release in 2010 [93], the Kinect has been adapted for a number of other uses and contexts ranging from a digital three-dimensional scanner to multiple guidance systems to help blind individuals navigate obstacles [94], [95]. The Kinect is a technology which provided new capabilities for interacting with the digital and physical world. These new capabilities changed the way users viewed the world and the activities which they could conceive and engage in—resulting in a variety of adaptations which are shaping the future direction of the technology.

Users have always changed, modified, and adapted artifacts and products, but the internet has enabled entire communities to develop around the modification of consumer products. Rather than an individual user's adaptations going only as far as word-of-mouth could carry them, the internet has provided the means through which users can widely disseminate their ideas. Publications like Make: Magazine [96], Instructables [97], and Life Hacker [98] have led the charge, serving as repositories of user–generated modifications, hacks, and original creations. Very specifically focused communities have also formed to support the adaptation of everything from photographic equipment (Strobist [99] and DIY Photography [100]) to Ikea furniture (Ikea Hacker [101]).

Figure 2.16: Examples of DIY photography modifications: a tilt-shift lens made from a showerhead and a rubber glove, and a soft focus filter made from a stainless steel sink filter.

This behavior is not limited to hobbyist markets. Highly trained professionals with significant experience and a detailed sense of their own needs, often adapt existing products rather than living with the limitations of current products. Surgeons adapting the Kinect for use in the operating room is just one example of this behavior. In his book *Democratizing Innovation*, Eric Von Hippel offers a number of examples of "lead users" changing technologies to better meet their needs and expand their capabilities. His examples are drawn from a wide range of contexts: from industrial products like printed circuit board CAD software, library information systems, and surgical equipment to consumer products like mountain bikes and other "extreme" sporting equipment. He states that, "…although most products and product modifications that users or others develop will be minor, users are by no means restricted to developing minor or incremental innovations." And that there is, "…strong empirical evidence that product development by user firms and users as individual consumers is frequent, pervasive, and important." [102]. Even in situations in which workers have little choice about which products to use, they frequently "…modify, work around, or even reject the artifacts provided to them

when [they] poorly fit the demands of practice…" [80]. Regardless of the specific context, users and stakeholders of all types frequently adapt their designs to new and changing purposes.

Some designs go a step beyond, however, and attempt to actively support adaptation, encouraging users to make their own way, or participate in the development of the product. Products and sources such as open-source software, end user-development [103], lead-user development [84], [102], and open-source hardware all encourage user adaptation in order to bring products into a closer fit with goals, desires, and context of use. Many of these projects rely on the power of contrasting perspectives, and treat designs as "experiments" [68], embracing the unknown and dynamic future while empowering the ability of other perspectives to adapt their artifacts to the rapidly changing environments.

Since the initial release of the Kinect, Microsoft has encouraged users and companies wishing to modify and adapt the Kinect by releasing the Kinect software development kit for Windows, in 2011. This kit allows developers to write Kinect apps in C++/CLI, C#, or Visual Basic '.NET', and greatly increases the ability of users to modify the product and broaden potential application contexts. Microsoft, as an organization, has changed as a result of the Kinect, and now has divisions of the company devoted to exploring these new modes of interaction in a wide range of emerging contexts—from interactive entertainment to business. These divisions are intended to pursue innovation and new contexts that were opened by the introduction of the Kinect, and will no doubt continue to build on a number of the novel directions identified by the devices initial users and adapters.

Another example of designing specifically to encourage user adaptivity is the Arduino microcontroller. The Arduino circuit board was originally conceived by Massimo Banzi, a teacher at an Italian design school, in response to his students being unable to find an inexpensive micro-controller for robotic art projects. The Arduino is an example of open-source hardware—free for anyone to use, modify, or sell. The original Arduino board consisted of an open source hardware board with an 8-bit microcontroller, which ran a standard programming language and a boot loader that executed on the microcontroller. The Arduino, itself, exists to facilitate multi-disciplinary projects, and has appeared in DIY projects (featured prominently in Make magazine and Instructables.com), commercially sold devices, and educational projects at both the high school and college level.

Figure 2.17: The Arduino microcontroller.

Individual users have leveraged the Arduino's accessibility and power to do everything from allowing users to finely control their vehicle's performance to control and guide unmanned model airplanes. Commercially, the Arduino has been used to control a number of products ranging from the OBDuino [104]—an electronic gauge that connects to the on-board diagnostic in a car to display information like the RPM of the engine, speed, and detailed fuel consumption—to a product from Botanicalls, which monitors a house-plant's soil and phones, texts, or tweets when the plant needs to be watered [105]. In class room settings the Arduino has been used for a wide variety of robotic projects, and was used at Ohio State University in a second year Mechanical Engineering course to drive the timing and operation of a student produced air-motor [106].

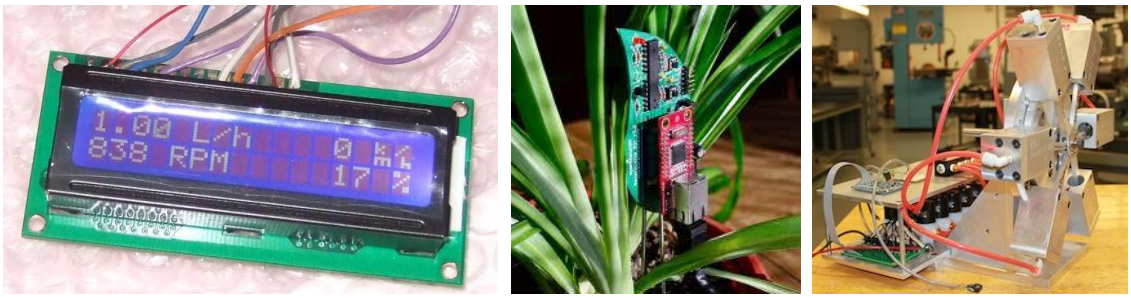


Figure 2.18: Arduino applications: the OBDuino, the Botanicalls device, and the OSU air-motor.

The Arduino's adaptability and openness are its greatest asset, and have taken the Arduino from the point where Banzi was unsure they would be able to sell 200 units (the first

production run), to the current state of the Arduino, in which there have been 500,000+ units sold. All in just six years [107]. But if the design of the Arduino is open, how does Banzi avoid his device becoming a commodity, in which his production can easily be under-cut by a foreign supplier? The answer to that question lies in the adaptive response of the Arduino's users. A sizeable community has developed around the Arduino board, and not only do they use it as a device to create adaptive projects, but they also adapt the Arduino itself—improving its functionality and modifying it for different contexts. These adaptations quickly find their way back to the central hub of Arduino: Banzi and the rest of the Arduino team. Because the Arduino is open-source, these design changes are implemented in future versions of the board, or even used to develop new boards [105]—as in the case of the LilyPad Arduino, a version of the board that is a physically-flexible, minimalist design intended for use in wearable projects. Since its introduction the Arduino has expanded greatly: sixteen official versions of the Arduino hardware have been commercially produced to date, each changing the functionality and providing new capabilities.

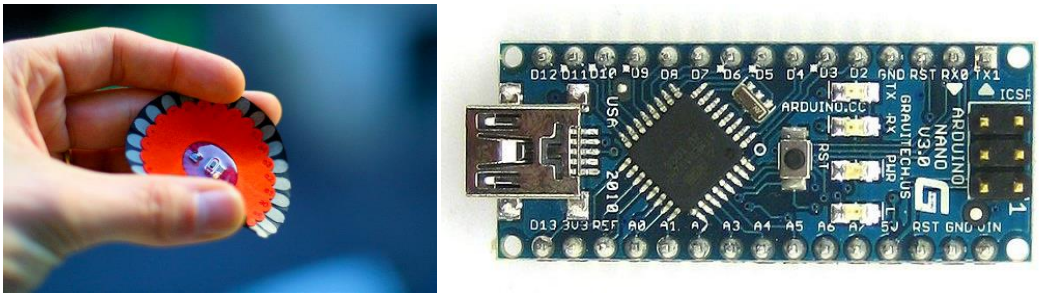


Figure 2.19: Arduino LillyPad and the Arduino Nano are two of sixteen commercially produced versions of the microcontroller.

Even with all of this rapid growth, which has resulted from the adaptive cycles that play out between users and the Arduino company, it seems as if Arduino is just getting started. As of this writing, the Arduino has transitioned from a niche item available only online to one that is being sold in retailers across America—the banner-ad at the top of the Make website advertises that "Radioshack now carries Arduino!" [108]. Further, the cascade of effects from the Arduino project is carrying over to one of America's largest companies. In an effort to provide similar adaptivity to their mobile phone users, Google has decided to follow Arduino's lead and launch the "Android Open Accessory Kit." This kit allows individuals to develop accessories and

modifications to smart phones running the Android operating system. Already a bastion for adaptive behavior with their open app-stores, users can now adapt the functionality of the devices themselves. With the introduction of the Open Accessory Kit, users can further adapt and transform their phones by developing new hardware and accessories. Maybe unsurprisingly, Google has selected the Arduino as the platform on which the Open Accessory kit will be based [107].

These interacting adaptive cycles are one of the factors that make complex adaptive systems so powerful. Product designs are no longer limited by what one perspective, designer, or organization can accomplish. Rather, the interconnectivity and interdependence of the system can build upon adaptive behavior from everywhere within the system—leveraging the knowledge and ideas from users, designers, manufacturers, etc. all of whom have differing, and diverse perspectives. The continued cycle of adaptive behavior ensures that the product can remain fit to the goals and needs of the field of activity, thus providing for the continued success of the product.

2.7.2 Decompensation and Failure

Because change is the norm in adaptive product systems, the same emergent behaviors and patterns that can lead to a product's successes can also lead to its failure. While companies strive for the rapid growth and runaway success that characterize complex product systems operating most ideally, that is far from the norm. Frequently, these same interdependencies and constant changes can lead to the emergent failure of a product—either in the form of functional failure, in which a design breaks or fails to perform, or more frequently when a design is replaced by an alternative that will perform better for a given context [45]. The complexity associated with the ways in which a system stretches upon the introduction of an artifact gives rise to unintended side effects, changes the nature of the task, and creates new paths to failure [44], [69].

Many products, upon their introduction, have the ability to deal with a range of inputs, users, situations, mishandling, and misunderstandings and still function effectively in the users' context and in the market [91], [109]. In other words, non-optimal designs can regularly perform "well enough" for users and continue to sell despite a range of circumstances that were unanticipated by designers or have changed since the product's introduction. Products can be

robust in the sense that, despite minor changes in usage or context, the product possesses the flexibility to meet needs and perform adequately for a range of situations, uses, and goals that it was not explicitly designed for. The fact that the design—as a hypothesis—is never completely correct does not in itself doom the product to failure, as users inherently satisfice—making do despite an imperfect fit between the artifact and their goals.

Today it is reasonable to assume that most designs will adequately perform the task, or tasks, that they were designed for; in order to make it to the market they possess some minimum level of functionality and meet the requirements for which they were designed. A mobile phone, for instance, will not make it to market without first being able to make and receive phone calls; at a bare minimum every phone will do these things reasonably well. But as users adapt to new devices, technologies emerge, new phones are released, and new expectations and desires arise, the product begins to become more and more out of phase with users and the context of use [70]. The product's context begins to look less and less like the world it was originally designed for—the designer's original hypothesis. Despite that, the design continues to work, it continues to function, it is still keeping up, it is still selling, and users continue to satisfice, adapting their behavior or the product in new ways to maintain its functionality for their needs and goals. Most users do not replace their mobile phones at the first sign of dissatisfaction or based upon the most recent shift in technology. Instead, users adapt their behaviors and methods in both small and subtle ways in order to continue to achieve their goals.

Eventually, however, the context and the stakeholders' concerns will evolve to the point at which the design can no longer meet the changed goals, needs, and desires of the user. This either results in the failure of the product, or in users moving on to a new artifact, which they perceive will better meet their needs. Frequently, this is the point at which design organizations recognize the inadequacy of their designs and step in, trying to save the design by producing a new version or a re-design. But at this point, it is often too late: the users have changed, and the world has moved on. While organizations can alter their designs in order to attempt to keep up, this often leads to products that are doomed to be out of sync with—and always chasing—the field of activity and constantly shifting user desires. This is representative of a pattern of failure common to all complex systems, called *decompensation*.

Decompensation refers to patterns of failure that occur when challenges increase and cascade faster than responses can be decided upon and deployed. Woods and Branlat describe a decompensation event accordingly [70]:

> The basic decompensation pattern evolves across two phases. In the first phase, a part of the system adapts to compensate for a growing disturbance. Partially successful initially, this compensatory control masks the presence and development of the underlying disturbance. The second phase of a decompensation event occurs because the automated response cannot compensate for the disturbance completely or indefinitely. After the response mechanism's capacity is exhausted, the controlled parameter suddenly collapses (the decompensation event that leads to the name).

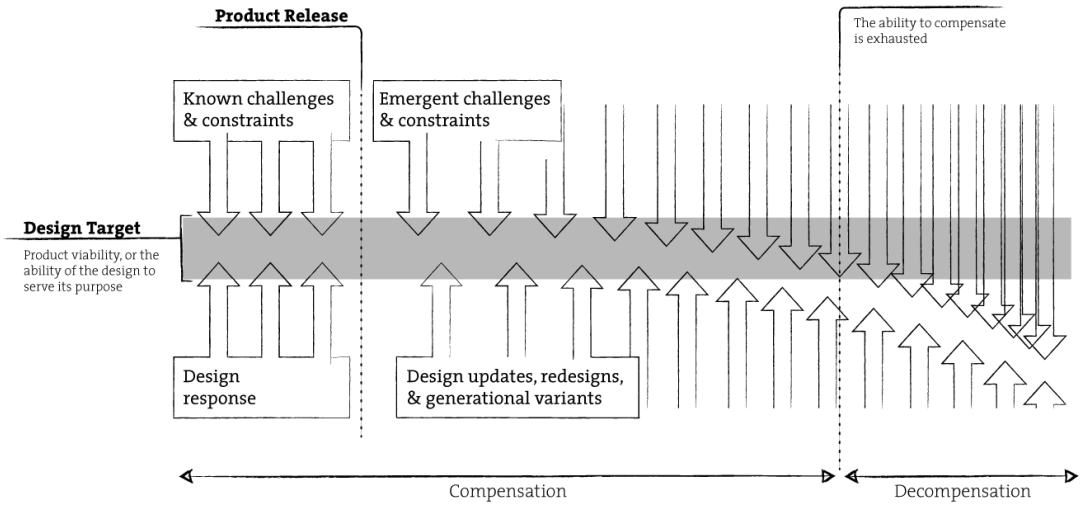


Figure 2.20: Product decompensation (adapted from Woods and Branlat [70]).

Every product is initially designed to fulfill a purpose in a given context. In order to meet that target, designers must address challenges, provide capabilities and meet user needs along a number of different dimensions. A well-designed product will address these factors in such a way as to adequately fulfill its purpose at the time of release. After release, however, new challenges arise and new needs emerge that must be adequately addressed in order for a product to continue to fulfill its purpose and remain viable. For a time, the original design is likely to be sufficient, and it will continue to satisfy users and serve its intended purpose, but eventually the desires and needs of users will change enough that the original design will show signs of no longer being able to serve its purpose or satisfy changing demands and expectations. Design

organizations respond by developing design changes, updates and new products in order to maintain the viability of the design. Depending on the ability of design organizations to recognize and anticipate these future challenges, it is possible to maintain designs for great lengths of time and over many generations of a product. But eventually the challenges and constraints cascade and change so significantly that the existing design and technology are no longer able to meet the demands placed upon it—the design organization has exhausted its capacity to compensate for the changes that are occurring in the surrounding system. This results in the failure of the product or users moving on to new and different products and technologies that better allow them to meet their changed expectations and desires.

What can designers do in the face of this pattern? Initially, it is up to designers to determine what may be useful given the wide array of possibilities that a new design embodies [68], but it can be difficult for designers to monitor and evaluate designs with respect to the many perspectives present within a field of practice. It is possible, however, to leverage the power of adaptive systems in order to deal with the challenges and take advantage of the opportunities that arise as the result of the evolving context and changing demands. Designers should strive to encourage the adaptive capabilities of users throughout the system, which may look different for every product. Whether users are actually adapting the products themselves or not is irrelevant, as it is surely possible to leverage the expertise and knowledge from a wide array of perspectives in order to learn about a design and its context. Doing so improves designers' understanding of what is valuable and relevant now, and into the future, thus allowing them to design products better fit to the *actual* needs and contexts of users.

Innovation is another way in which design organizations can avoid the failures associated with decompensation, as innovation represents a transition to a new target or purpose. Developing innovative products is a way to "reset" the entire product system (represented in *Figure 2.21*), allowing organizations to avoid many of the challenges associated with decompensation patterns. Generational products are an attempt to maintain the viability of existing designs, and therefore require organizations to monitor, anticipate, and recognize emerging challenges and demands—which can, at times, be very difficult. Innovating, on the other hand, identifies a new target or a new path to viability, and therefore establishes a new design or a new paradigm that is in less immediate danger of decompensation. However, innovating is easier said than done, and every attempt to innovate carries an increased risk of

releasing a product that is not aligned with the actual challenges and desires of the market, thus missing the target entirely [66], [79].

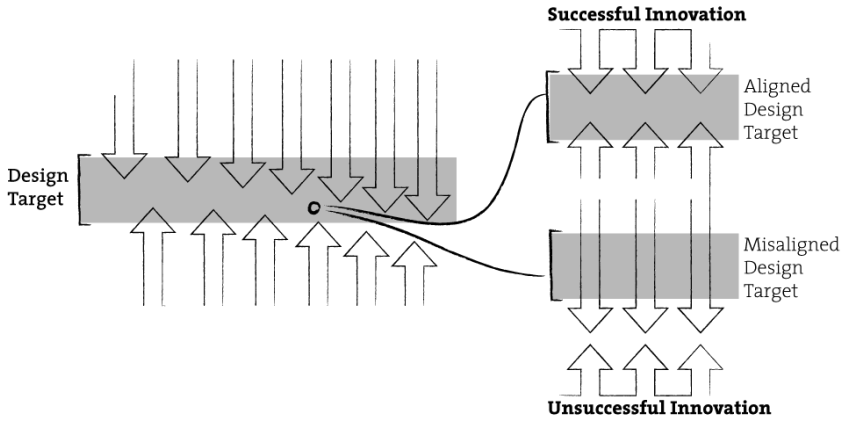


Figure 2.21: Innovation can help to avoid decompensation by "resetting" the product system, but innovation attempts are equally likely to miss the target.

Regardless of how a design organization attempts to manage the uncertainty and change that are innate in complex product systems, designers *must* realize that designs themselves have the power to initiate transformation. It is not just that these systems change and evolve in unpredictable ways, but rather that designs have the ability to initiate and direct change within the system. A design will inevitably alter the practices and purposes it was designed for, resulting in a new, changed system. At the same time, designs are still hypotheses, and designers are never entirely in control of them or the product systems into which they are released. Thus, if design organizations are better able to anticipate and support change (rather than trying to control or fight change), they are more likely to design products that initiate positive cycles of adaptation, leading to more successful, and resilient, products and systems.

2.8 A Brief Note on Trade-offs

Three critical trade-offs have been introduced that shape the design process within complex product systems: (1) *Local-global trade-offs*, in which designers have to attempt to balance the goals and outcomes of design decisions from their local perspective, with their *actual* effect on the complete product system. Balancing designs with respect to this trade-off often requires

viewing the system, and the problem, from multiple perspectives. (2) *Acute-chronic trade-offs*, in which designers must balance the immediate, and easier to quantify goals of the design process (time, cost, etc.) with longer term system goals (quality, innovation, sustainability, etc.). (3) The *optimality-brittleness trade-off*, which specifies that designs cannot be optimal with respect to every factor or constraint. Inherently, every design will be well aligned with respect to some constraints and less well aligned with others—it cannot do everything equally well for all contexts. As a design becomes better adapted to some context or activity, it inherently becomes more mal-adapted to some other dimensions.

But even with those trade-offs enumerated, it would be remiss not to point out the prevalence, and importance, of trade-offs within complex adaptive systems, and more specifically, complex artifact systems [70], [91]. In many ways, the design process is a gigantic balancing problem, in which the designer must consider the three trade-offs listed above, while balancing an innumerable number of constraints. Every design decision has implications across the artifact system and over time, and progress in one direction can never be achieved without losses somewhere else. Every design decision carries some trade-off cost, and, as the old saying goes, there is "no free lunch". It is easy to achieve a satisfactory understanding of this concept with a simple context independent example: In an attempt to improve a design, designers might decide to construct an artifact out of aluminum instead of steel, in order to make it lighter, easier to carry, easier to lift, or easier to use.

In an attempt to reduce weight, however, designers sacrifice the potentially necessary durability and strength afforded by steel. In an effort to both reduce weight and maintain strength, designers may explore the possibility of producing the artifact out of carbon-fiber, but doing so is likely to increase cost, complicate material sourcing, and increase the complexity of the artifact's fabrication. This increase in cost may alienate some of the product's target market; and so on. So which combination of criteria and potential design decisions, should the designers prefer? There is never a single right answer. In this way, every design decision embodies give-and-take, and it is the designer's job to balance any final solution within the space defined by these sort of trade-offs.

The reason a simple, context independent example is highly effective at conveying the essence of trade-offs within the design process is because this concept is innately understood by almost anyone who has ever designed anything. It is the *reality* of design. In order to produce any

object, these types of trade-offs must be considered and balanced, and the negotiation of design decisions across trade-offs occurs in every design problem. But in real-world design activities matters are complicated considerably as the trade-offs are rarely as linear and clear-cut as in the example above. Instead, the amelioration of these trade-offs is difficult as they are often difficult to even identify and understand, as the trade-offs only emerge as the result of interactions that occur throughout the product system. These interdependencies and trade-offs are not solely internal to the design, and design decisions frequently affect aspects that touch every corner of the system—decisions with regard to an artifact's manufacture, may embody trade-offs with the artifact's use or the user's hopes and dreams, for instance. This is in many ways, the fundamental nature of design in complex and interconnected product systems.

2.9 Telling the Whole Story—Design as a Co-adaptive System

In the introduction, it was stated that this chapter would attempt to integrate relevant concepts into a cohesive story representing the designer's struggle with complexity; ultimately making recommendations about how these struggles can be overcome. But as one has likely deduced, these complexity challenges are not the sort that can ever really be overcome *per se*. Trade-offs, uncertainty, and change are all principle parts of complex product systems, and are, as such, unavoidable. Rather than striving to overcome them, designers and design organizations must figure out how to better understand and manage the ways in which complexity impacts their particular design processes, and the associated design performance.

2.9.1 More than Just a Product

Complex product systems are comprised of artifacts (both the design in question and other artifacts), adaptive agents (designers, users, manufacturers, secondary users, etc.), and the context environment (that includes the activity, physical environment, market environment, etc.). However, product systems are not reducible to their structural components in the physical domain (the hierarchical structure of the artifact) as a result of interdependencies that exist between the artifact and the world. Attempting to understand a product system by studying the artifact, the users, or the activity in isolation will lead to an incomplete picture of the product system's true nature. Nor can product systems be understood solely on the basis of past

performance, needs, or interactions between previous artifacts and the world—"the history by which they came to be" [17]—as the world changes as a result of the artifact's introduction. Rather, an artifact system can only be understood in the interplay between the artifact's structure and currently evolving constraints that emerge as we move into an uncertain future.

Accordingly, designers must not be concerned with just the artifact, the interplay of its component parts, or even the artifact and a user. Instead, design organizations must focus their efforts on understanding the larger unit of design, which encompasses all of the interactions among the design, the artifact's users, and all of the contexts and activities in which the design is expected to perform. Recognizing that while designers must frequently study these elements in relative isolation, it is the interactions among them that actually drive the behavior and performance of product systems. But even if design organizations define their focus in such a broad way, they must be aware that product systems are ultimately dynamic. They change over time and every component of the system—whether designer, user, artifact, or culture—exists in an environment comprised of all of the other components of the system [16]. Because of this, every component can exert an influence and result in changes to other parts of the system, or the system as a whole.

2.9.2 Designs Can Initiate Unpredictable Change

Because every part of a product system has the ability to alter the overall system, designers must recognize the role of products as vectors of change. The introduction of a new design will alter many things about the system, ranging from the way people work, to the activities that they can perform, to their emotions, goals, purposes, and dreams. The introduction of an artifact can change everything about the system, and the system with the product in it is fundamentally different from the system prior to the product's introduction [7], [17], [89]. In this way, problems, activities, and goals that were the initial focus of the design process are changed by the product itself—the output of the design process [16]. As such, no design is perfect for its environment, every system stretches, and change is inevitable.

The paths of change that a design initiates are often wholly unpredictable, and despite their role in initiating change, no designer can ever anticipate all of the ways in which a design will be used, or how it will transform the field of practice. Artifact systems are certainly complex,

and designers are asked to envision and balance the effects associated with the introduction of a product into highly interconnected systems comprised of humans, cultures and organizations that each make decisions and adapt their behavior in order to meet goals and needs within highly dynamic fields of activity. In this context, it is only possible to produce successful and meaningful designs if designers are able to understand the product system from multiple perspectives, as designs are ultimately understood in the context of a user's activity, and across multiple scales. The performance of every design is tied to a litany of interacting factors and perspectives that must be weighed and balanced. Each perspective on the product system, each user, and every context imposes unique constraints that will combine to determine the artifact's ultimate success or failure (regardless of how you choose to define those terms). Users throughout the system purchase and acquire designs in order to accomplish goals and needs within their fields of activity. They do so by using products to perform a wide variety of activities and tasks that do not have simple one-to-one relationships with features of the product. Use is a complex phenomenon, and it is a mistake to think that designers can accurately anticipate, or predict, how an artifact will affect the system; it is more problematic still to think that designers can control it [46].

Because of this, designers must realize that they are in a position to fundamentally transform the contexts for which they design, despite the fact that they can never fully know the adaptations that a design will undergo. Adaptations and effects cascade throughout the system, sometimes leading to positive results—new markets, user participation, and increased sales for example—while other times leading to breakdowns and failures that ultimately doom an artifact. At the same time, all designs do not transform the system to the same degree [17]: Many designs only initiate minor transformations and lead to relatively few adaptations, simply improving some small aspect of the product system. But other designs, like the Arduino (or the personal computer before it) can initiate powerful cycles of transformation and adaptation that radically change the structure and interconnections within an artifact system, thus enabling future adaptations, artifacts, and innovative opportunities.

2.9.3 Complexity is a Framing, Not a Design Method

Complexity, and complexity science, are not in and of themselves a way to design, or any sort of design method. A grounding in complexity is necessary in order to understand product systems, as they are one class of a much larger category of complex adaptive systems. But complexity methods are less than ideal when trying to balance the numerous trade-offs and constraints that are inherent in the design process—they are not in any way a *substitute* for design. When attempting to identify and understand real-world design problems, and envision possible futures and innovative directions, a designer's creativity and intuition cannot be replaced. However, the framing provided by an understanding of complex adaptive systems may be invaluable in helping designers to recognize the interconnections and interdependencies that matter. In turn, this can help organizations to envision artifacts that open new opportunities and provide capabilities that support, rather than hinder, use and adaptivity. The challenge, then, is to move away from "theories of what," and move towards "theories of how" [110]; transitioning from an understanding of complex product systems to a focus on doing, creating, and making within complex product systems—in other words, the act of design. In this way, this chapter establishes the background (the 'what'), and sets the stage for the rest of this dissertation which is concerned with designing in this context (the 'how').

An understanding of the structure and mechanisms that underlie complex product systems can help design organizations to anticipate and avoid breakdowns, but we must recognize that it is never possible to anticipate and design for *every* possible future. It is the nature of all design activity that we must identify and select a finite set of constraints, problems, and opportunities on which to focus our efforts and resources. The goal, then, must be to better identify the critical interdependencies, and to better anticipate the ways in which breakdowns may occur given a specific focus—providing designers with the tools and procedures necessary to cope with the dynamic world. Designers' focus needs to be on learning how to adapt, and how to encourage adaptation along paths that will bring the design into a closer fit with the current needs and constraints of the field of practice, while simultaneously looking to open new opportunities and directions.

How are designers to actually accomplish these things in practice? A daunting task for certain, but methods, approaches, and strategies can be developed in order to help designers to

balance the multiple perspectives and constraints that arise from positions and scales throughout the product system. Doing so in a way that is useful within *actual* design practice requires recognition of the complexity phenomena that make product systems simultaneously challenging and powerful. Interconnections, uncertainty, emergence, and adaptation are certainties within product systems, and are, in conjunction with artifacts, users, and contexts, responsible for their behavior. In this context the goal of design organizations must be to simultaneously leverage design as a transformative tool (shaping the future), and as a strategy to manage inevitable and unexpected change. In order to do this, it will first be necessary to develop a detailed understanding of the space in which all designs exist—more specifically, a way to explore and categorize all of the factors that make up the larger unit of design.

Chapter 3: Design and Constraints

3.1 The Nature of Constraints

The underlying goal of most design disciplines is to conceive and implement the design, fabrication, and operation of artifacts to meet perceived real-world needs. In almost every case, design outcomes are embodied in something tangible—a product, system, or process—that attempts to resolve a problem/opportunity in a non-trivial way. *Non-trivial* because designed artifacts do not exist in isolation: in order for a design to be successful it must adeptly balance the many contextual factors—from performance requirements and market trends to the activity and the environment of use—that define every unique design problem. By looking more closely at these factors, it is possible to gain a deeper understanding of how they impact both the design process and the process of educating beginning designers. In doing so, insights will emerge that will lead to a better understanding of the design process, design performance, design education, and the evolution of designed artifacts. This understanding may then be leveraged in order to yield positive benefits for the way in which problems and opportunities are formulated, understood, and addressed through the execution of the design process.

In this chapter, a constraint-based model of the design process will be outlined and described. In this view, the 'constraint set' is viewed as a determining element of the design process, which helps to define how design is done, how it is taught, and how it evolves over time. This set of constraints is a direct result of the fact that designed products are embedded in complex adaptive systems. The set of constraints both reflects, and assists in the analysis of the structure of real-world design problems. These constraints result from, and affect, all of the components that make up the larger unit of design—stakeholders, context, and the artifact. Individual constraints exist both within and without the artifact, and are controllable to varying degrees [55], [111]; in every case, factors such as consumer preferences, manufacturing processes, material properties, technology, and the design process itself all give rise to constraints that affect the design process and the artifact.

Constraints also exert a profound influence on the processes and methods used to generate relevant design knowledge. Everything from broad and well-established design standards to problem specific design research is in some way constrained, or propelled, by factors related to the context of creation and adoption. In this way, constraints shape the artifact itself as well as the knowledge and skill that conditions the artifact's creation. Because understanding and managing specific constraints very often calls for particular knowledge or skills, constraints also affect the structure of the design team. While a design team cannot hope to predict every constraint that they will encounter over the course of a single design, the constraints that are known at the outset will necessitate the inclusion of certain types of expertise and thus, team members. The reverse is equally true: the composition of the design team can, and will, affect the constraints that are recognized and addressed throughout the design process.

A useful way of thinking about constraints is to build a framework of categories that helps the design team to organize their thinking about constraints. Ideally, the constraint-based model of the design process presented here will assist both practitioners and educators in the exploration and resolution of design problems in all of their variations—serving a valuable purpose throughout the design process. In any case, the value of highlighting design constraints arises not as some abstract descriptor of how the design process works, but as a way to better understand and manage the effects of complexity on the creation, adoption, and performance of artifacts. This fact cannot be overstated, as understanding and managing the effects of complexity on the design process and artifact performance is, at its core, the focus of this dissertation. It is also central to any theoretical or pedagogic value this dissertation may hold. Accordingly, the rest of this chapter will be devoted to explicating the constraint-based structure that serves as the foundation for the dissertation.

It is also important to note that this dissertation takes an expansive view in how the term 'constraints' will be defined and used. The traditional connotations around the term 'constraint', both within the design community and in standard practice, tend to portray them as unavoidable restrictions on the design process, on potential solutions, or on the artifact itself. There is also a tendency to view constraints as something inherent to the design problem, which existed long before the design process actually began—they are, in this view, pre-existing, static, and resistant to change, either by designers or users. In a more authentic view of the design process, constraints are more negotiable than traditional wisdom allows, and their manipulation is an

integral part of how designers explore solutions and manage the complexity of real-world design problems [55], [111].

For our purposes, constraints include all of the desired, inherent, or imposed properties of the world that have specific consequences on the properties of the artifact as it relates to design, manufacture, performance, and use. As they are recognized and applied throughout the design process, constraints shape both the designers' understanding of the space in which they are designing, and the possible outcomes of the process. Constraints provide much needed structure to the essentially infinite space of design possibilities, and serve to limit as well as expand possible outcomes.

The view of constraints outlined here embodies two primary types of constraints: *inherent constraints* and *imposed constraints*. *Inherent constraints* are those constraints which are unavoidable and often arise from the very nature of the design problem. In practice they are often referred to as hard constraints—things such as material properties and laws of nature. Conversely, *imposed constraints* are those that are applied to the design problem by organizations and designers—more often analogous to goals, opportunities, and requirements. These imposed constraints vary to the degree in which they are able to be affected by designers—with goals frequently being more discretionary and more mutable than requirements. Constraints imposed by governmental regulations, for example, are far less negotiable than those constraints applied by the designers themselves in order to guide the search for a solution. But regardless of their origin, these constraints all share the fact that they are not integral to the problem itself—they are to some degree controllable by the adaptive agents involved in the specification of a design.

If we regard constraints as factors that are occasionally flexible and able to be affected by designers—instead of factors given in advance—it is possible to envision design scenarios in which the constraints are not fixed at the outset of the project. Certainly, there will always be inherent constraints that are out of designers' control—Newtonian physics, safety requirements imposed by an outside organization, or the cost to purchase and shape a certain material, for example. Beyond these are many constraints that are selected and imposed by designers in order to make sense of a problem, explore the design space, or to establish a solution—as is the case with a product's price point or the relative size and weight of a specific component. This view of constraints more accurately depicts research on actual design processes in which all of the constraints are not given as instructions or requirements [55], [112]. The constraints imposed by

designers are every bit as essential in reaching high-quality design outcomes as those constraints that are strictly outside of a designer's control. Constraints manifest themselves both as factors inherent to the design problem that limit what is possible, and as a powerful tool through which designers can explore possibilities, shape the design space, and open opportunities for innovation.

Whether inherent or imposed, constraints often serve to limit possibilities and define the design space. While designers, and especially design students, may chafe at the idea of any limits on their imagination, design constraints actually provide a necessary benefit to designers, by greatly reducing the number of viable solutions, thereby directing and focusing their efforts. Constraints, for example, are the difference between telling someone to design 'something', and to design a 'vehicle'. While there are a greater number of possibilities, designing 'something' is considerably less tractable than designing a 'vehicle.' Deciding to design a 'vehicle' immediately introduces constraints about the function which the design must perform—it must now transport people or goods. This simple distinction narrows the design space, focusing the designers' thoughts and cognitive activity.

'Vehicle,' however, still embodies an enormous number of options and potential directions, with everything from a wheelbarrow to an airplane being viable possibilities. If we continue to specify our design problem further, by focusing on the design of a 'car', we are imposing additional levels of constraints—a self-propelled vehicle capable of land travel—that provide greater structure to the problem. Going a few steps further, we can set out to design a car (a four wheeled automobile) that is powered by an internal combustion engine. In doing so, we continue to impose constraints and continue limiting the problem, making it more and more tractable—which is why this level of thinking and specification is frequently the starting point for many design processes. Nonetheless, imposing constraints further limits the potential solutions. Our design problem, defined as an internal combustion automobile, obviously precludes the concept of an electric car. In every case, this constraining and specification is a necessary part of the design process, as design is most easily conducted, and original ideas most easily generated, when a problem is specified at the appropriate level of detail.

Giving structure to both the problem and the solution is a large part of what it is to design [64], and in this way constraints provide a way for designers to affect and navigate the design space—defining the boundaries of what is possible based upon designers' current

understandings and goals. Defined in this way, constraints are neither positive nor negative. They can be both an obstacle and an advantage. What is critical is how they are understood and manipulated in order to produce successful and innovative design solutions. While certain constraints are unavoidable and must be confronted, in most instances designers are free to define and impose constraints in order to better structure both the problem and solution [55]—that is, constraints are equally applicable to both the design problem and the artifact itself.

When designers understand constraints as a boon to the design process, it is possible to achieve new levels of understanding and innovation. But by accepting constraints as an integral part of the design process—and designed artifacts as a solution to a problem posed by a set of constraints—we are in no way trying to write creativity or skill out of the design equation. Simply focusing on constraints in some specific way is not, in and of itself, a formula for successful design. Rather, designers rely on skill and creativity *within the boundaries* of their constraints. Even while armed with a better understanding of the contexts that constrain their designs, no small measure of personal skill and creativity is required in order to develop innovative and successful products. In fact, design history is filled with examples of new or challenging constraints that, when placed in the hands of talented designers, quite often resulted in brilliant designs [113].

The design of the Mini Cooper is an example of a highly innovative design which emerged from a tightly constrained design space. The original Mini Cooper, made by the British Motor Company (BMC), is a small economy car that was first produced in 1959. The Mini is widely regarded as both a breakthrough design and an automotive icon to this day. Its innovative space–saving design allowed 80 percent of the vehicle's floor plan to be used to house passengers and luggage—making the most of a tight space and thus influencing an entire genre of vehicles [114]. The Mini was not simply conceived out of thin air, but instead emerged as the result of a very specific set of constraints, imposed by the time and place of the vehicle's design, the Mini's competitors, and one of BMC's outspoken leaders.

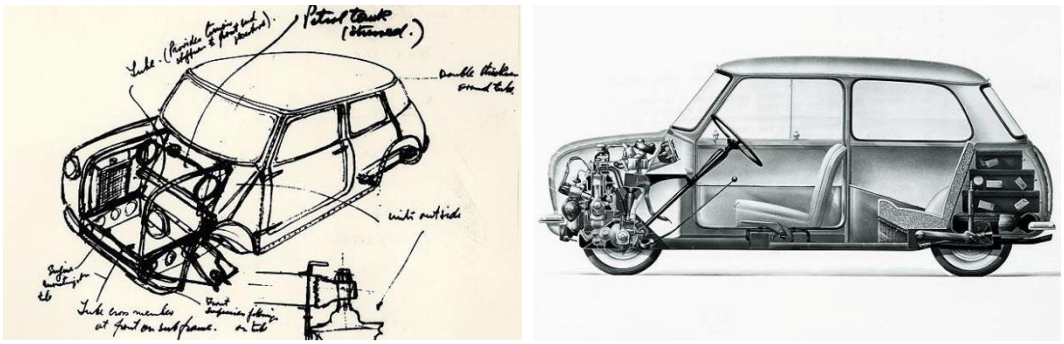


Figure 3.1: The highly constrained, highly innovative Mini Cooper: design sketch by Alec Issigonis (1958) and vehicle cross section [115].

In 1956 the Suez fuel crisis led to gasoline becoming a rationed commodity in the UK, and car sales slumped as refueling became increasingly impractical and unaffordable [116]. As the market for full size cars declined, the market for more fuel efficient 'bubble cars' grew rapidly. Bubble cars were extremely compact vehicles initially exported from Germany by former military aircraft manufacturers like Messerschmitt and Heinkel; they were eventually produced in Italy, France, and the UK as well. As these vehicles continued to be imported in greater numbers, the head of BMC, Sir Leonard Lord, took exception to these preposterously tiny vehicles, and vowed to produce a "proper miniature car" in order to rid the UK's streets of the bubble car [117]. Beyond constraints imposed by fuel prices, efficiency, and the culture of post-World War II UK, Lord also set forth an extremely tight set of physical constraints for the design of the vehicle. The "mini" vehicle had to be contained in a box that measured no more than ten feet long, four feet wide, and four feet high [118]. Within that space the passenger and cargo components would measure eight-and-a-half feet in length, leaving an "impossibly small" amount of space for the vehicle's power-train.

To navigate these constraints, Lord turned to Alec Issigonis, who had previously worked for BMC. To preserve as much interior space as possible, Issigonis "…chose a front-wheel-drive configuration, mounted the engine transversely, and developed a new transmission that was so tightly mated to the engine that the two shared their lubrication. Issigonis also employed a novel suspension system, designed by inventor Alex Moulton, which replaced coil springs with small rubber cones…" [117]. The final vehicle offered surprising room, power, and handling to go along with impressive efficiency. The former president of Chrysler Corp., Bob Lutz, stated, "The

Mini was the progenitor of all of the small cars that came afterwards. I mean all of them" [119]. In 1999, a jury of 126 auto experts representing 32 countries voted the Mini the second most influential car of the 20th century, trailing only the Ford Model T [120].

Figure 3.2: A Messerschmitt KR175 "bubble car" contrasted with original Mini Cooper.

In his *How Buildings Learn*, Stewart Brand recognizes the value of tight constraints in design and innovation. Writing primarily about buildings, Brand recognizes that constraints on the design process can actually be freeing, providing direction and focus to the designer by narrowing the design space. In discussing why the modification of old buildings is more frequently successful than designing new buildings, Brand states [46]:

> This is the formal answer to the question, why are old buildings more free? They free you by constraining you. Since you don't have to address the appalling vacuum of a blank site, you can put all of your effort and ingenuity into the manageable task of rearranging the relatively small part of the buildings mass that people deal with every day — the services, space plan, and stuff. Instead of having to imagine the plans, you can visualize directly in the existing space. 'We'll need another window over there to light this room, which will be much deeper when we take out that wall. And then those stairs will be more central, so we should make them a bit grander.' It is much easier to continue than to begin. Less money is needed, as well as less time, and fewer people are involved, so fewer compromises are necessary. And you can do it by stages while using the space. The building already has a story; all you have to do is add the interesting next chapter.

Whether running through a quick thought experiment, as in the case of designing 'something' versus designing a 'vehicle,' or real world examples like the design of the original

Mini Cooper and the modification of existing architecture, it is clear that constraints can help to frame design problems. By inserting constraints, designers can better direct their efforts and open new parts of the design space for exploration and experimentation. Constraints have the ability to establish the boundaries and structure of a design problem, thus providing designers a jumping off point from which to explore and define the rest of the artifact.

In addition to their role in directing new opportunities, constraints can also serve to explain the differences between designs. In this way, constraints are a major generator of variation within a market, or product segment. Variation amongst designs can be seen in almost every market and class of product, as in the differences between all of the vehicles on the road today from pick-up trucks to sports cars, as well as in the smaller variations between Ford and Chevy trucks. More broadly, variation can also be seen across what George Basalla refers to as, "…the vast universe of objects used by humankind to cope with the physical world" [82]. That is, the difference between a Chevy truck and a cell-phone, or a cell-phone and blender. Both types of variation—within a class of artifacts and across all artifacts—are a vital part of how designed artifacts, as a whole, are able to meet such wide variety of human needs.

The power of constraints in differentiating designs will be quickly illustrated using a very simple example: the two dominant types of personal computers, desktops and laptops, are both designed in order to provide the same basic capabilities, and at a functional level are very similar. The constraints on these two devices are nearly identical in almost every respect except one—the laptop's overwhelming need for portability. Because this single constraint is so crucial, the artifacts themselves are wildly different. The laptop has taken on an extremely integrated architecture, combining the input devices (track-pad, keyboard, etc.), the output devices (display, speakers, etc.), and the increasingly miniaturized internal components (circuit board, hard drive, battery, etc.) into a very closely-knit artifact. Unsaddled with the constraint of portability, the desktop computer has taken on a form whose internal components are highly modular. The desktop's power supply, fans, drives, graphics processor, etc. all exist as relatively independent components, as do its input and output devices—with monitor, keyboard, mouse, and speakers existing as separate products altogether. The portability constraint in the design of these two products has led to significant differentiation in the form of the design solution.

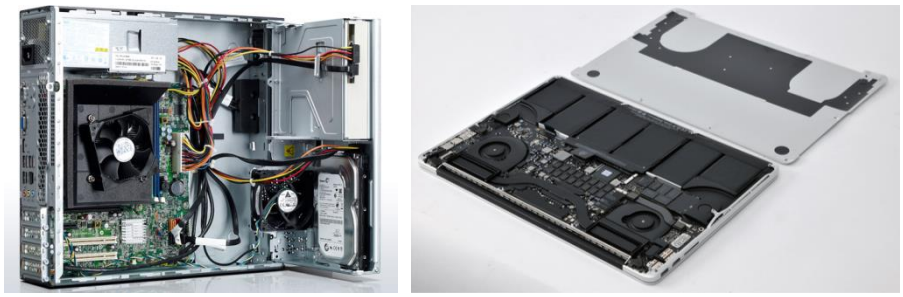


Figure 3.3: A difference in constraints has led to significant differentiation between desktop and laptop computers.

Even among directly competing artifacts—two laptops or two desktops, for instance—there is often a large degree of variation that can be seen. These differences are sometimes subtle and sometimes vast, but they can all be tied back to the constraints that are present within the artifact, or that exist within the design space surrounding it. The constraints which a design team recognizes and chooses to focus on often play a large role in explaining why no two designs look exactly alike. Constraints explain why, given the same problem, design organizations will consistently produce solutions that are, in their details, quite dissimilar. Different levels of importance attached to individual constraints account for why there exist a vast array of cell-phones, bicycles, and cutlery on the market today—each one different from all other made objects that have ever existed. Ultimately, many of the differences among designed objects can be explained as a result of the way in which designers go about identifying, and subsequently accounting for, the relevant constraints.

It is evident to anyone who has looked critically at the designed world that these differences exist—and that they are the result of different constraints, and different perspectives on those constraints. For even the simplest of artifacts, for example the disposable, single–use coffee cup lid, this principle applies. Locked in place on a disposable cup, it is intended to prevent spillage while helping to retain heat. This would seem to be a design problem so simple that, once a satisfactory solution has been identified, it would never need to be revisited. Since the earliest patents were granted, however, a curious thing has happened: the number of designs for disposable cup lids has exploded. While obtaining a precise count of the number of novel lids designed is exceedingly difficult, it is possible to offer a rough approximation: one collector alone has amassed more than 550 varieties [121], and the actual number is likely to exceed one

thousand in the U.S. alone. What can possibly explain the sheer number of designs for an object as simple as a disposable coffee lid?

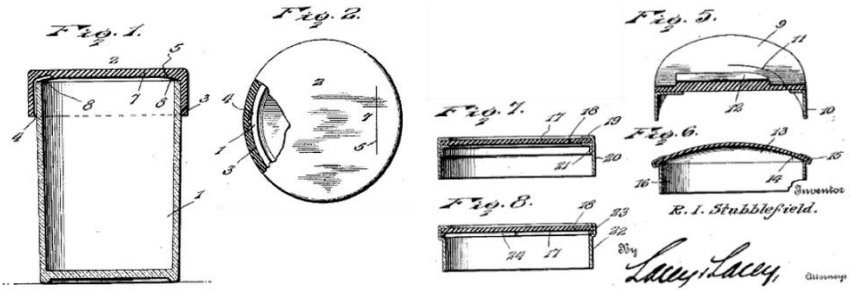


Figure 3.4: The "Stubblefield lid" likely represents the first patent issued for a disposable beverage lid, was issue in 1934.

At first blush, the disposable beverage lid does little more than prevent spillage and maintain temperature, but under closer inspection there are a host of additional constraints that must be considered and balanced in order to design such an object. One of the very first patents for a drink through lid was granted in 1934. The "Stubblefield lid" was designed to allow children to drink beverages without spilling [122], but was a far cry from the highly complex injection molded lids of today. In what is quite possibly the first "contemporary" design for a disposable coffee cup lid (U.S. Patent no. 3,206,059 [123])—filed on September 13, 1962—the inventors' claims list a host of constraints that apply to this seemingly simple object: disposability, liquid does not splash or seep out during normal handling, lightweight, inexpensive to manufacture, breaks the capillary passageway between the lid and cup wall surfaces, prevents migration of the liquid around the lip of the cup, permits the escape of air and water vapor so as to prevent an elevated pressure condition within the cup, and if the liquid becomes cooled prevents the creation of sub-atmospheric pressure which would interfere with the removal of the lid.

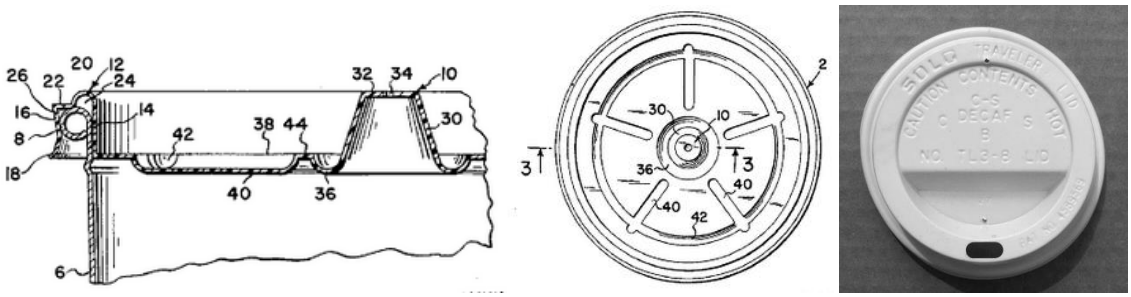


Figure 3.5: Drawings from Fead and Huff's patent and possibly the most famous coffee cup lid ever designed, the Solo Traveler.

Since that time, many additional constraints have been identified and leveraged in the design of disposable coffee cup lids. In search of a better way to contain hot liquid in a disposable cup, designers have explored tear-out and open varieties of drink through lids (like the renowned Solo Traveler), multiple-piece re-sealable lids, and lids that change color in order to indicate temperature, just to name a few. Each design variation represents a solution to a problem posed by a certain subset of possible constraints that was chosen and balanced by designers, likely based upon the goals of clients and the perceived desires of users—in this case coffee drinkers and suppliers. This view of the design process, based upon constraints, gives rise to a new understanding of the disposable coffee cup lid – one in which design historian and coffee cup lid collector Phil Patton remarked at, "…how many varieties there were, how various and intricate the device is and how intensely designed they are" [124].

Figure 3.6: Just a few of the many designed variations of coffee cup lids, each addressing different constraints in different ways.

Constraints drive product variation in three primary ways: (1) constraints can be addressed differently by different designers, (2) different constraints are identified and differently prioritized by designers, and (3) different constraints are inherent within different design problems and opportunities. Given the exact same constraints there are certainly multiple ways for designers to achieve a solution, as different designers can leverage constraints in different ways. But constraints are perhaps the most interesting when considered as the set of factors that defines the context in which a design exists. Although it is impossible to fully identify every relevant constraint, it is easy to see how recognizing relevant constraints, followed by some manner of prioritization has become a large part of the design process. It is "…unlikely that rival firms and designers [will] all read the context in exactly the same way" [54], as different designers give priority to different parts of the larger constraint set—and this, in turn, leads to a wide variety of diverging design solutions.

While this adequately explains most of the variation that exists within a class of objects, there is yet greater variation that results from the different constraints that are inherent within specific design contexts. A set of constraints is one of the primary factors that differentiate one designed artifact from all other man–made forms. In fact, one could argue that any design solution can be uniquely explained as the result of a constraint set distinct to that particular context and the designer's formulation of the problem. Alongside goals and objectives (which can, themselves, be seen as imposed constraints), the constraints inherent to a design opportunity represent not only the difference between a desktop and a laptop, but also the difference between a laptop and a toothbrush, or a desktop and an automobile. The constraints, identified by designers, exert an influence on each process, and are at least partially responsible for the final form and configuration of every single artifact.

3.2 A Constraint Framework

Whether speaking of the constraints that are inherent within a design problem or those imposed by designers, the impact of constraints on the design process—and, in turn, a design's performance—is undeniable. Constraints exert an influence over everything from problem setting and ideation to applicable manufacturing technologies and logistics networks. While constraints powerfully impact design, we must remember that they both empower and restrict,

constraining the design space while opening new avenues of exploration and innovation. We must also recognize that many constraints are not a direct result of the artifact itself, but are instead due to the surrounding context, the field of activity, or the artifact's usage. In the design of a tea kettle, for example, the artifact must withstand and transfer energy to the liquid contained within—this is a functional constraint inherent within the artifact. But it is certainly possible to design a tea kettle that transfers energy to the water, but does not have a handle—the introduction of this "requirement," or a similar constraint which allows for the hot liquid to be transferred without harm to the user, arises as the result of the goals of the user and the surrounding context.

Because of the complexities and interactions inherent in any real-world design process, the full set of constraints that will impact the design of an artifact can never be fully enumerated. The designer's limited time, understanding, and perspective ensure this fact. Further, after a design is introduced into the context of use, we can never know all of the factors that contributed to its success or failure—even post-mortem analyses and other studies of how and why designs succeed or fail are inevitably limited. Given that even after an artifact's release we cannot identify every relevant constraint, then certainly designers will never be able to anticipate every relevant constraint prior to its introduction.

The act of design embodies hypotheses about the underlying set of constraints: what are the relevant constraints? How should they be prioritized? How should those constraints be addressed and balanced? The goal of this chapter is to set forth a constraint framework that can help designers of all types to organize and explore these concepts, and assess the impact that constraints have on their designs. Even without enumerating every single constraint, there is considerable value in this exploration—particularly, with respect to a designer's holistic understanding of the larger unit of design. At the same time, a certain level of fidelity is necessary in order to build an authentic picture of a given context. If used in a shallow or oversimplified way, this framework will provide a greatly reduced opportunity for learning, and is unlikely to lead to a deep understanding, or the recognition of novel opportunities.

The constraint structure put forth here is intended not as a model of the design process, or even as a design heuristic, but rather as a *scaffold* through which designers can more effectively understand and leverage the full range of factors that impact their designs. It is the product of a great deal of thought, and has been subjected to application in a number of different test cases

[113], [125], and has been found valuable over years of teaching and researching design in both engineering and industrial design contexts. This constraint structure has also been shown to be useful in discussing product architecture, design evolution, and the performance and management of designs over time (*Chapters 4 & 5*). It also provides the basis for the constraint–based design management tool proposed in *Chapter 6*.

As constraints can be both ill-defined and overwhelming, what has been devised is a rational system which will aid in the study, understanding, and application of constraints in both research and application contexts. This framework has led to the creation of constraint categories that can be used to specify and understand any constraint in a deep and relevant way. The basic claim is that all of the constraints which affect, and are a result of, physical artifacts can be viewed and explained as a combination of five fundamental constraint categories. These fundamental categories are: physical, technological, market, socio-cultural, and usage. The rest of this section will serve to define and further explain each of these fundamental categories.

In working through these five categories of constraints, it is important to remember that the true value of this framework arises not from these five specific labels or a prescribed application of this format, but rather from the framework's ability to assist designers in understanding and managing the complexity inherent at the intersection of the artifact, the field of activity, and the design process. In contrast to many models of the design process, which "…do not fully take into account the environment in which designed products should perform… [and instead] focus on the individual aspects of the design in isolation" [126], this constraint framework attempts to understand design opportunities in a holistic manner—accounting for the full range of factors that will influence the design's creation and performance. By using this framework, designers will be better able to understand their position within a complex design space, and better able to manage the trade-offs inherent within every design process.

Before continuing, it is important to note that the impact of constraints on the design process is not, in and of itself, inherently novel. To date, quite a lot has been written about the importance of constraints in the design process. Herbert Simon [38], takes a more formal view of constraints as a way to optimize a design for a set of known constraints and objectives; Stewart Brand [46] talks about the importance of constraining a design problem with respect to architecture; Bryan Lawson [111], makes the distinction between internal and external

constraints (those arising from the artifact and those arising from the design context, respectively); Christopher Alexander [4] advocates for one of the most all-encompassing views of constraints, saying that constraints, "…can be as various as they need be, and do not have to be restricted only to requirements which can be expressed in quantifiable form." Alexander's definition of constraints most closely matches the view of this dissertation: in order to reflect the true nature of design performance, a multitude of factors must be accounted for.

While the idea of constraints on the processes of engineering design is not novel, little has been done to propose a framework that will assist engineers and designers in the task of identifying and prioritizing the most relevant constraints for a given design task. To the best of the author's knowledge, neither has anyone looked at design constraints as a way to facilitate trans-disciplinary communication. By negotiating these constraints across disciplines, a shared view of the design problem may be developed, increasing buy–in and devising solutions that are better balanced across the full set of factors relevant to a design's performance. The central goal of this chapter is to outline a flexible constraint model, which can help to track and communicate authentic understanding of the ways in which constraints interact in the actual design and implementation of physical products.

3.3 Specifying the Five Categories of Constraints

Every real design exists within a world of constraints. Accordingly, specifying the underlying structure—a taxonomy of constraints—may prove useful in facilitating a deeper understanding and furthering discourse with regard to constraints, and design practice in general. Again, it is my contention that these five categories of constraints—physical, technological, market, usage, and socio-cultural—represent the most basic set of constraints. While every constraint encountered by designers will certainly not fit neatly into these five categories, I claim that every constraint can be constructed and explained as a combination, or derivative, of these five general categories. The intention is that these categories provide a manageable and accessible set of building blocks through which designers can construct a holistic understanding of the design situations that they routinely encounter.

In working through the categories of constraints, the reader will likely recognize that the constraint categories and the individual constraints appear to fall on a continuum that ranges

from concrete to abstract. While this is in no way empirically verified, the constraints do in fact *appear* to follow a particular pattern in which the physical and technological constraints tend to be more concrete—closely tied to quantifiable metrics and hard quantitative data. In contrast, the use and socio-cultural constraints frequently seem more abstract—often relying on qualitative data, intuition, and designer's own personal insights. Market constraints, then, seem to sit alone in the middle of this continuum, in that they are sometimes concrete and quantitative—as in the case of a price points, budgets, and overhead—and sometimes quite abstract, as in the case of proprietary positions and brand identity. This categorization is not a hard-and-fast rule, but rather is presented for its perceived value to the reader—potentially allowing for more rapid understanding, and a better mental organization of the five categories of constraints.

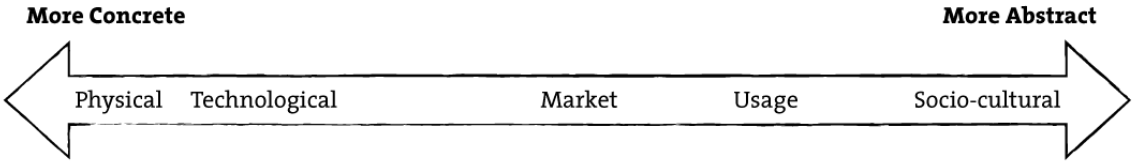


Figure 3.7: Constraints tend to range from concrete physical and technological constraints to abstract socio-cultural constraints.

Because theorizing about the design process can so easily wander off into useless abstraction, we will attempt to ground the discussion with as many product examples as possible. In addition to the category specific examples provided, the example of a digital single-lens-reflex (DSLR) camera will be used with each of the categories in order to give a better sense of how these constraints interact in the design of a single artifact. This product has been specifically chosen because DSLR cameras possess both hardware and software components and embody a sufficient, but manageable, level of complexity.

Figure 3.8: The Nikon D70 is just one example of a digital single-lens-reflex camera (DSLR).

3.3.1 Physical Constraints

Physical constraints are characterized by factors such as weight, volume, density, strength, rigidity, conductivity, etc. In many ways, these constraints define the physical limitations on the artifact, and are often the result (or the cause) of the materials and processes used in its fabrication. Typically, physical constraints do not appear in detail in the early stages of the design process—as they are frequently determined by other, higher level, design decisions—but instead, they emerge gradually as the design progresses. For example, it is difficult to make decisions about the weight or size of a component until we have some understanding about what functional requirements will be placed on that component. The case surrounding an external hard drive, for example, serves the functional purpose of protecting the hard drive's sensitive internal components from damage or shock—as in the case of the Red Dot Award winning LaCie *Rugged*, which was designed by Neil Poulton as a shock-proof, highly durable hard drive designed for the harsh conditions of travel and use. This intended functionality gives rise to far different weight, size, dampening, and strength constraints than does a hard drive whose case is primarily designed to serve an aesthetic purpose while it sits on a desk. However, these constraints only emerge and differentiate themselves after designers have made decisions about what the functional role of the hard drive.

Figure 3.9: The LaCie Rugged hard drive is designed for a different set of constraint than most external drives, and this is reflected in the drive's construction and aesthetics.

While physical constraints are not typically dominant in the early stages of the design process, there are certainly exceptions. When a particular physical constraint is critical to the design performing its intended function, it typically appears much earlier in the design process. This most often arises for constraints like size and weight when performance—or more specifically, performance directly related to some physical property—is a critical issue in the artifact's valuation. For example, in the design of many portable electronics like cell-phones, tablet computers, and laptops, the size and weight of the device is frequently a critical factor. As such, the design of all of the device's internal components—the hard drive, main board, battery, memory, etc.—must all fit within a specified footprint or volume. In the case of a smart-phone, the volume available for the internal components is tied to the size of the case, which is frequently tied to the desired portability and the size of the phone's display. In this instance, designers understand very early in the process that the combined size of the components must be contained within a limited amount of space in order to achieve certain levels of portability and performance per unit size.

Other instances of functionality, pushing physical constraint definition earlier in the design process, often arise when performance per unit of mass is critical. Sporting equipment, vehicles, airplanes, and spacecraft are all associated with high performance, which can only be improved by addressing physical constraints. In the design of the Mars rover *Curiosity*, for example, NASA was forced to balance an extremely complex set of constraints. *Curiosity* is an approximately car-sized robotic rover that is part of NASA's Mars Science Laboratory mission (MSL), whose main goals are to help study Mars's climate and geology, determine the role of water, and help prepare for possible human exploration [127]. For any device that is required to

"climb out of the gravity well of the earth," total mass is the number one constraint—so long as there is not a human on board (safety is clearly the dominant constraint in that case). Accordingly, the mass of the rover was a primary constraint that had to be dealt with from the outset of the design process. Every ounce, screw, and design decision had to be meticulously considered in order to finally arrive at a highly integrated solution that could escape the earth's atmosphere [128].

Interplanetary travel also necessitated that the rover could be safely deployed once it arrived at its destination, and physical constraints were once again paramount. In particular, designers at NASA were forced to continually minimize the rover's mass in order to ensure the successful entry, descent, and landing on the Martian surface. If the mass was too high, entry velocity would exceed the physical capabilities of the parachutes intended to slow its descent. This could lead to the chutes tearing, or an inability to sufficiently slow the rover prior to landing—resulting in an impact that would destroy the craft. Accordingly, everything on *Curiosity* had to be designed with this in mind. If the rover came in too "hot" and did not survive the landing, every other part of the design would be unable to fulfill its intended purposes. No matter how well designed these other pieces were, the mission (and the design) would have been a catastrophic failure.

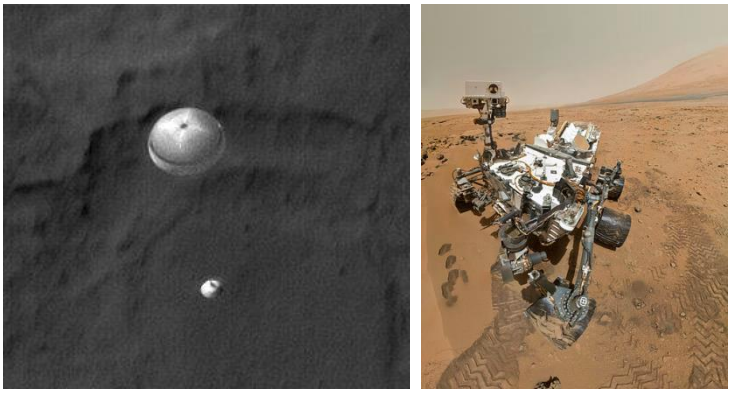


Figure 3.10: Curiosity descending under its parachute, and the rover on the Martian surface. Curiosity demanded high performance per unit mass, and therefore physical constraints occupied a prominent position throughout the design process.

Physical constraints are also frequently tied to constraints of use. This is true for both the physical interaction that occurs between an artifact and a user, and the functions that an

artifact performs 'internally', i.e., without human contact. In the first case, constraints on size, shape, weight, etc. are frequently determined by ergonomic factors. Cell phones, for example, must be small enough to fit in the user's hand, and carried in a pocket throughout the day. At the same time, the phone itself and the means of interaction (the buttons or touch screen) must be large enough to allow for the phone to be grasped and controlled. The marketing campaign for the iPhone 5 emphasized the fact that its touch screen display was perfectly suited to the human hand [129], with one commercial stating: "Your thumb, it goes from here… to here. This bigger screen goes from here… to here. Now, that's either 'A', an amazing coincidence, or 'B', a dazzling display of common sense." Beyond interacting with the controls, it is necessary that the distance between the earpiece and the phone's mouthpiece fall within a certain range, so as to allow a wide range of users to be able to simultaneously speak and hear. Cellular phones are a perfect example of how physical constraints are established by the human/artifact interaction—too big and a cellular phone becomes cumbersome and unwieldy, too small and it is hard to hold and impossible to interact with.

Figure 3.11: Stills from the iPhone 5's marketing campaign, showing that the phone's physical size was driven by usage constraints.

Physical constraints also arise as the result of the functional tasks an artifact is intended to perform. This has less to do with physical ergonomics, and more to do with the constraints that arise in meeting the goals, needs, and expectations of a specific user. In order for any product to hold value, it must accomplish something that matters to the user. In the case of the LaCie *Rugged* hard drive, one specific functional task is quite different from most other external drives. In order to facilitate travel, durability, and rugged use, the designers of the LaCie drive addressed a number of additional physical constraints that would not typically be considered in

the design of an external drive. These constraints led to a unique aluminum shell, a disk-drive mounted on four independent suspensions, and a thick rubber bumper. All of these design features have led to the LaCie *Rugged* being well received by a host of demanding users, ranging from photographers to emergency service personnel [130]. It is often these constraints, driven by functional demands, which make up a large part of what we typically consider physical constraints.

Physical constraints can also arise as the result of interactions with factors external to the product. These interactions can be between the product and other artifacts—giving rise to constraints on interfaces, volume, etc.; the artifact and its associated manufacturing processes—leading to constraints on material selection, or aspects of the physical design resulting from specific processes, fixturing, quality control [131], etc.; or the artifact and the environment in which it will be used—leading to constraints on material choices, corrosion resistance, toxicity, etc.

While physical constraints are legitimately the domain of many design disciplines, beyond material selection and considerations of size and shape, the detailed design decisions related to these factors tends to be the province of engineers, who devote a considerable part of their formal education to learning how to analyze and manipulate physical constraints. That is not to say that industrial designers or architects are in any way blocked from exploring new possibilities as they relate to these constraints, nor are they incapable of addressing them. Rather, these are the constraints that most typically fall under the "ownership" and control of engineers.

Referring to the digital SLR camera, we see that a certain level of strength, rigidity, and opacity is required in order to protect the internal components, facilitate interaction, and shield the light sensitive components of the camera from unintended exposure. While the first two constraints may be obvious physical constraints that arise in most products, the opacity constraint is more unique to the design of a camera. Without due consideration to this constraint—which affects material selection and thickness, and the ways in which components physically interface with one another—it would be impossible to produce a camera that effectively accomplishes its primary function: capturing and storing an image. Each of these elements, however, is affected by more than just opacity. Material choice, for instance, is also affected by strength, rigidity, conductivity, and durability constraints, not to mention the 'touch

and feel' aspects that result from the design language of the camera. Thus, some set of feasible materials is specified by the intersection, and interaction, of these constraints.

The strength and rigidity of the camera body is also determined by factors that extend beyond material selection such as its structure, manufacturing methods, size, and shape. At the same time, the overall size and weight are also constrained on the high end by what a photographer is able to reasonably carry and operate (its usage), and on the low end by the necessity to house all of the essential components. One could certainly make an incredibly durable camera case out of half-inch stainless steel, but it would be unlikely that many people would lug it up the side of a mountain, which is where that durability is necessary in the first place. One could also reduce the size of the internal components in order to allow the camera to be smaller and lighter, but this would entail a similar reduction in the size of the image sensor and the focal length. Doing so, however, would effectively reduce image quality, which is one of the primary reasons photographers choose SLR cameras over smaller point-and-shoot cameras or cell phone cameras.

Additionally, the detailed design of the camera body is constrained by the fact that it must be compatible with the system of lenses produced by that particular manufacturer. The interface, by which lenses are attached to the camera body, ensures that all Nikon produced SLR lenses are compatible with every Nikon SLR, just as every Canon SLR must mount all Canon produced lenses. In satisfying this interface compatibility, camera bodies are constrained the historical design decisions that are embodied within a lineage of cameras and lenses: every Nikon lens produced since the late 1950's is mountable to even the newest digital SLR cameras. Continuing the exploration of constraints, each of these camera lenses are of course also subject to the physics of light and optics, as well as the material properties of the glass, polymer, aluminum, and stainless steel of which they are made.

As a category of constraints, physical constraints represent a sizeable portion of the factors that are frequently thought to make up the design space. Physical constraints inevitably lead to decisions on everything from material selection and manufacturing, to the object's functional capabilities and user-interaction. As they frequently result from the product's intended functionality and use, physical constraints tend to exert a larger influence as more design decisions are made and designers progress deeper into the process. While physical constraints are

an extremely important piece of the full constraint set, they never represent the *only* type of constraint that exerts an influence on the design of an artifact.

3.3.2 Technological Constraints

Technological constraints are imposed by the state of technology at the time of the artifact's design. In its most common use, technology refers to "a capability given by the practical application of knowledge" [132]. In design, *practical* application is key. More specifically, technological constraints relate to how designers and organizations can leverage the current state of knowledge in the design and production of artifacts. Implicit in this definition is that technological constraints stretch well beyond the cutting edge electronics that are most frequently associated with the term, and include most applications of current knowledge.

In this sense, technological constraints may represent factors that are both material and immaterial. Material technological constraints are those that are embodied in actual artifacts, and include not only traditional high-tech constraints with respect to electronics—things like processing power, memory, and speed—but also constraints that refer to the current state of the art in materials, mechanical configurations, power, and performance. There are, however, technological constraints that also deal with factors such as techniques, processes, systems, and methods of organization that are purely knowledge–based, and are not attached to specific physical constructs. New manufacturing processes for example open new possibilities and impose different constraints than the processes which they replace. In both material and immaterial cases, however, technological constraints are frequently a corollary of science and engineering, in that these fields are often responsible for the *change* in technological constraints.

Since technology and technological constraints are based upon the application of knowledge 'at the time' of the artifact's design, it should also be clear that these constraints shift over the course of time. The constraints that existed when designers sat down to create the earliest consumer cellular telephones, for example, are clearly quite different than the constraints confronted by Apple when it designed the first iPhone. When it was released in 1983 the DynaTAC 8000X was the first commercially available handheld cellular telephone. At the time, it was the result of fifteen years—and one-hundred-million dollars—worth of research, provided the user with thirty minutes of talk time, an LED display, and enough memory to store thirty

phone numbers and went on the market for $3,995 [133] – $9,400 adjusted for inflation. This was clearly a very different constraint environment than the one that Apple confronted when they began the development of the original iPhone in 2005 [134]. In fact, from the physical size of electronic components and the state of display technology to the feasible range of transmission and the established communications networks in which these devices are embedded, nearly every technological constraint has changed in the 24-year span between the releases of these two phones. The differences between these two phones go well beyond technological constraints, but the influence of various technological constraints is undeniable. Without even opening the phones up to reveal their internal components, many of the effects of technological constraints can easily be seen.

Figure 3.12: Comparing the original iPhone to the original mobile phone (the DynaTAC 8000X), reveals a quickly changing set of technological constraints.

Technological constraints are, in general, closely coupled with market constraints. Similar to market constraints, and in contrast to physical constraints, technological constraints have the possibility to change rapidly. Largely due to the direct correlation with current state of knowledge, technological constraints appear to be in a near constant state of change. This change may be the result of competitors and competitors' products, external factors such as cutting edge research, or even technology emerging from distant and unrelated fields. Beyond changes to technological constraints from competitors and other external sources, these constraints also change as the result of a firm's own products—with design decisions that address technological constraints setting a new bar, and opening new possibilities, for every product that is subsequently released.

While it is easy to view technological constraints as applying only to the artifact itself, they can also emerge from all of the other systems which surround and support the artifact: the technology related to design, manufacturing, distribution, service, remanufacturing, and recycling all have the potential to constrain the development and market introduction of the product. The design process is impacted by technological constraints through the tools and methods that are available to designers. One might assume that the design process will proceed, one way or another, with the tools available at the time. While this is certainly true, the tools and methods available to designers absolutely influence possible design directions, as well as the speed and efficiency with which designers can explore those directions, and the sophistication of any analysis performed during the design, e.g., stress analysis for a structural component. For example, it is hard to discount the productivity and capability–related gains—associated with changed technological constraints—that have resulted from introduction of the computer into the workplace. More specifically, changing technological constraints related to new software tools, or new research methodologies, have led to changes in design outcomes. Tools like CAD software, CNC machining, and rapid prototyping technologies have all had large impacts on the design of engineered objects.

In his book *What Engineers Know, and How They Know It*, Walter Vincenti recounts how the introduction of new design methods transitioned airfoil design—the surface of an airplane wing whose shape and orientation influence stability, direction, lift, thrust, etc.—from a non-systematic process of trial and error into a much more precise activity [45]: "The introduction of thin-airfoil theory in 1922 allowed an airfoil section to be analyzed in terms of an infinitely thin *mean* (the line halfway between the upper and lower surfaces) plus a… varying *thickness distribution."* This had a significant impact on the design of airfoils and airplanes, as this theory caused a basic shift to the constraints on the design process, allowing engineers to work at a new pace and efficiency. "Before, airfoil designers drew or otherwise defined an airfoil's shape according to experience and judgment, with hope it would give suitable lift and drag…." Now, designers could synthesize airfoils with approximately predictable lift characteristics, and more systematically design and test families of aerodynamic profiles. Note that the actual physics – which imposed physical constraints on the airfoil design – did not change. The *technology* of calculating these physical constraints did change, and significantly affected every subsequent airfoil design.

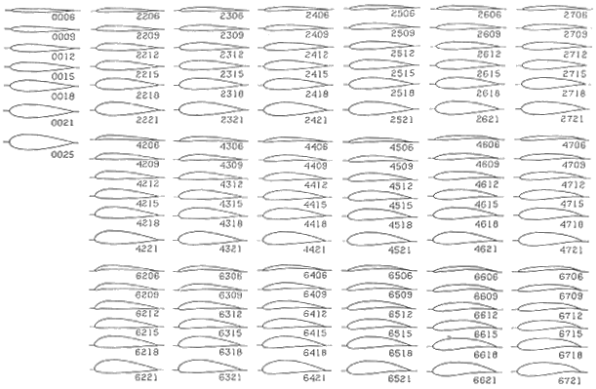


Figure 3.13: Before the introduction of new methods, a vast family of airfoils (above) would be designed using trial and error methods [45].

Other examples of how technological constraints apply to both the artifact and the associated processes can be seen in manufacturing technology. Firms and designers that are limited by the current state of the art in manufacturing technology routinely confront technological constraints, and can even explore novel design directions based upon changes to those technological constraints in the realm of manufacturing and assembly. Constantly improving fabrication techniques has allowed manufacturers of integrated circuits and microchips to continually miniaturize feature sizes (transistors, resistors, capacitors, etc.), and thus pack more circuitry onto smaller and smaller chips. This allows greater performance and efficiency to be built into electronic devices, which has revolutionized the design of physical products.

While the introduction of new manufacturing technology provides new opportunities, it frequently brings with it new constraints and challenges as well. As feature size shrinks, purity and contaminants become increasingly problematic; integrated circuits are constructed under vacuum, and the air is filtered to remove elemental, molecular, and other particulate contaminants [135]. In order to produce the latest chips these clean rooms have become increasing clean, and companies like Intel and AMD invest billions of dollars to match their fabrication capabilities to the pace of changing constraints [136].

It is also important to note that technology constraints can be either global or local, in that they may apply to all designers within an entire industry or only locally to a single firm or

organization. While to this point we have primarily discussed technological constraints in the global sense—the larger 'state of technology'—it is certainly possible for technological constraints to apply to individual organizations or design processes. These local technological constraints are most frequently imposed by the organization as the result of internal capabilities, lack of organizational knowledge, or cost. An organization, for example, may not have the process know-how, skill, or funding to procure or implement the materials, manufacturing technology, or human capital necessary to accomplish a given objective within the design process. As a result, a technological constraint exists for this organization, which may not exist for other, better-equipped organizations. In effect, these factors can function as technological constraints within a particular design process, despite the fact that these same factors may not be constraints within another organization, or another industry.

Looking at how technological constraints have influenced the DSLR camera provides a number of examples, as these constraints touch almost every piece of its design. Many of these constraints are related to the image capture process in a digital, rather than film–based media. During the outset of the digital revolution in photography, the technological constraint that was most obviously and most actively challenged by manufacturers was the number of effective pixels that the camera used to capture an image. Most often measured as the camera's number of 'megapixels' (one-million pixels), the state of this technology was evident to consumers because it was one of the primary metrics used by manufacturers to market digital cameras. The number of effective pixels is itself affected by other constraints on sensor size (physical), the state of digital sensors (technological), pixel density (technological), and the desired image quality with respect to both film–based images and competitors' products (use and market respectively) just to name a few.

Manufacturers like Canon, Nikon, and Sony were constantly confronting these technological constraints in order to expand the capabilities of their cameras and in turn, their users. In this way, this specific technological constraint morphed into a market constraint as well, with a sort of "megapixel race" emerging, in which all of the manufacturers were essentially forced to keep pace with the number of megapixels being offered by their competitors. While megapixels are an accessible numerical approximation of image quality for consumers, by themselves they are not sufficient to determine the quality of a digital image. At some point, the returns on increasing a camera's number of effective pixels began to diminish—Nikon admitted

that the megapixel race ended around 2009 when cameras were able to achieve 10-12mp [137]—while other technological constraints began to assert themselves as more important to image quality. As the number of megapixels reached a sustainable level, the focus of designers and engineers shifted to the development of "quality" within the sensor: constraints that dealt with factors such as sensor speed, digital artifact reduction, high-ISO sensitivity, and aliasing then became more prominent. Similar stories can be told with relation to the manufacturing of the sensor—particularly as it related to miniaturization—as well as the camera's interaction with related technologies such as flash systems, wireless controls, and camera control software.

One result of ever-changing technological constraints, is that artifacts end up being technology *snapshots*—pictures of a particular state of technology and knowledge, frozen in time. Every artifact, whether the Neanderthal's simple stone tools or today's high-tech electronics, is embedded with information about the state of technology at the time they were designed and produced. This information is carried with the product as long as it exists, and actually provides us with a record through which we can track the movement of technological constraints over time. In his book *The Evolution of Technology*, George Basalla meticulously tracks the evolution of stone tools, hammers, barbed wire, smoke stacks and any number of other technologies [82]. While he is focused primarily on "progress" and the evolution of artifacts, he is ultimately tracking the movement of technological constraints, and how, over time, the change of these constraints affects the design and implementation of an artifact.

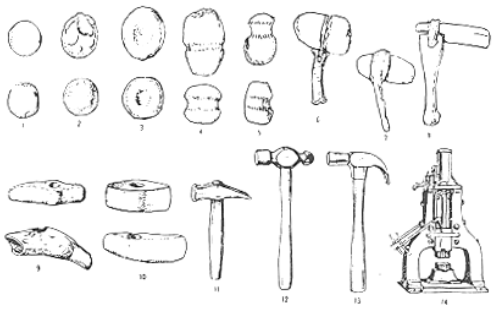


Figure 3.14: The evolution of the hammer from simple stone tools to the steam hammer; each is a snapshot of the technological constraints at the time of its creation [82].

When viewed together, technological and physical constraints give rise to the majority of the factors which can be viewed as *internal* to the artifact: those constraints which exist in the artifact that are relatively independent of the larger unit of design. While constraints like the strength and conductivity of a material, or the physical and technological laws that govern all artifacts, can be viewed as separate from the context of application or use, that is not entirely so. All of these constraints are still only relevant insofar as they afford some opportunity or capability to an artifact's stakeholders in the context of use. In this way, even seemingly concrete technological and physical constraints are closely tied to more abstract constraints relating to an artifact's use—further evidence of the inseparable nature of constraints.

3.3.3 Market Constraints

Market constraints in design almost always begin with cost and time to market, but in general they are much more involved than that. In fact, this constraint category is quite large and complex, comprising factors related to cost, spending, timing, clients, competitors, regulations, and legal concerns that exist both internal and external to the designing organization. Factors such as competing designs, the development budget for a project, the size and layout of the manufacturing plant, and the expertise of the firm and its competitors all fall into this category. For established designs, or those that are a component of a larger designed system, market constraints are often the most significant class of constraints. The importance and influence of these factors on real-world design processes cannot be overstated, but all too frequently they become the primary focus of a design process, in effect limiting the exploration that is allowed to occur with regard to the other categories of constraints.

When discussing market constraints, it is important to note the difference between those which originate from factors *external* to the design organization, and those that are primarily *internal*. When we think of the 'market constraints' on an artifact or design process, the first factors that come to mind are often the external monetary costs incurred during the artifact's production. Items such as material costs, overhead, machine costs, and production costs and factors such as consumer cost, profitability, margins, and time to market typically spring to mind. These are the external factors which contribute to the design organization's ability to sustain the other costs associated with the design and production of an artifact. Under most circumstances,

each of these factors helps to define the space in which designers may explore possibilities and pursue alternative designs. Each of these can also be closely tied to other external factors that originate outside of the design organization, as clients, suppliers, and competitors all have some influence over the market constraints that exert themselves within any design process. Consumer cost and first to market concerns, for example, are obviously tied to competitors' products. In order to be first to market, an artifact must inherently beat some other product to market, and every design is judged against its competitors in the open market. This leads to situations in which consumer cost is often dictated as much by a product's competition, as it is by factors relating to the artifact's production and distribution.

The original Xbox gaming console, for example, was sold by Microsoft at a considerable loss—estimated at $125 per console—in order to gain entry to a market that was dominated by Sony's 'PlayStation 2' and Nintendo's 'GameCube' [138]. While the practice of selling consoles at a loss is certainly not unheard of—as a part of a loss-leader strategy, in which the firm attempts to turn a profit based upon game and peripheral sales—the Xbox price-point was directly constrained by its more established competitors. In fact, Microsoft ended up investing more than $4 billion in the original Xbox. This investment was necessary for Microsoft to enter the existing game-console market; doing so paved the way for Microsoft's second console, the Xbox 360, which led to a game business currently creating over $1 billion in yearly profits for Microsoft. The Xbox and its successors have been Microsoft's "…most successful diversification to date," and are positioned at the center of Microsoft's home entertainment strategy for the foreseeable future [139].

Additionally, in situations where an artifact is not produced entirely "in house" clients and suppliers typically engage in some manner of quoting or bidding process, which is constrained on one end by the supplier's costs of production, and on the other, by competing bids and competition across multiple suppliers. Because of the tight interconnections between competitors, competing designs, suppliers, and manufacturers, market constraints can often change quite rapidly—the result of both technological innovation and the behavior of highly competitive products and organizations.

Internal to any single organization, there are market constraints that arise from factors such as project budgets, funding, project scope, team size, team structure, and the resources (monetary, physical, technical, software, or knowledge resources) available to any given design

project. These market constraints internal to an organization are almost always connected to and influenced by other external market constraints. A project's budget or the available resources, for instance, are almost always determined by the expected return or a negotiated contract between the design organization and a client.

Beyond these more obvious connections, the interactions between internal and external market constraints can influence the design process in more unexpected ways as well. In the design and production of the Boeing 787 Dreamliner, Boeing relied heavily on an entirely new organizational structure. The final assembly of the 787 was to occur in Boeing's Everett, Washington facility, but instead of the traditional process the 787 final assembly revolved around the integration of components and systems designed, engineered, manufactured, and assembled by a host of global contractors. Boeing instructed these global contractors to perform more of the manufacturing and assembly, and deliver completed sub-assemblies to the Everett, Washington facility. In addition to a leaner and more efficient assembly process [140], one of the primary drivers of this effort was the intentional diversification of suppliers. In order to more effectively sell and operate the plane in a global economy, different parts of the plane were designed and manufactured in a variety of different countries. While this resulted in a truly global artifact, this ultimately caused a number of problems for final assembly (delays, poor fits, quality issues etc.), for the Dreamliner itself (most notably in issues regarding the batteries, electrical systems, and wing), and for Boeing as an organization (public perception, perceived quality, etc.).

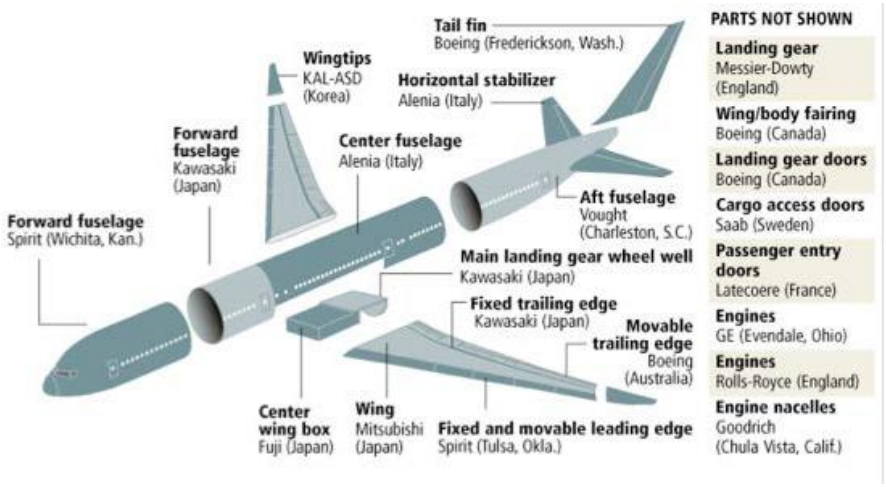


Figure 3.15: The varied origins of the assembled components of the Boeing 787 Dreamliner.

Internally, the design activities within an organization need to align to facilitate activities occurring in the proper order, and with the proper timing. This occurs notably in manufacturing, where certain components and sub-assemblies are required in order to build the larger assemblies. Accordingly, those operations must be completed first, but similar coordination is required in the design process itself. For instance, certain activities must occur before others in such cases where the information product of one activity is a necessary input to begin the next activity [141]—design research for example is most effective as a precursor to actual design activity. Later in the process, the analysis and evaluation of variant design concepts cannot be conducted until the concepts themselves are first generated. These outputs of concept generation—whether in the form of sketches, physical models, or digital models—will be used as an input to the processes of analysis and evaluation [141]. These types of market constraints typically manifest themselves on the design process itself, more so than the artifact, but by influencing the process they, in turn, exert an influence on the artifact in an indirect way.

These timing and coordination–related constraints arise as the result of interaction with external factors as well. External suppliers, clients, and their associated processes are some of the most notable sources of these constraints. Dell Computer grew to become one of the most profitable companies in the world by blurring the lines between suppliers, manufacturers, and consumers. Their innovative organizational model allowed Dell to enable "…coordination across company boundaries to achieve new levels of efficiency and productivity." This model, which Dell called *virtual integration*, achieves the advantages of a tightly coordinated supply chain (vertical integration) coupled with the expertise of highly specialized and focused suppliers, by "…stitching together a business with partners that are treated as if they are inside the company." This structure allows Dell to take custom orders received directly from consumers and deliver a finished computer in a matter of days, while keeping inventory at very low levels. For instance, rather than taking standard deliveries of a component designed and manufactured by a supplier, shared information and the tightly knit nature of these relationships allowed Dell to say, "Tomorrow morning we need 8,562, and deliver them to door number seven by 7 A.M." In order to facilitate this sort of just–in–time production Dell and its suppliers had to function *as* a single organization, by sharing data and working in concert with one another.

This level of coordination, inconceivable prior to the birth of the internet, is responsible for the creation of a host of new market constraints on designers, as precise timing and coordination are becoming increasingly important within design, manufacturing processes, and supply chains. Even the final delivery of the Dell computers is a highly coordinated dance. When a Dell computer arrives at a user's door it is important that every piece arrive simultaneously so that the computer is immediately usable. Dell does not actually design, manufacture, or assemble computer monitors, so this places a number of additional constraints on the delivery of both computer and monitor. As Michael Dell boasted in a 1998 interview, "We tell Airborne Express or UPS to come to Austin and pick up 10,000 computers a day and go over to the Sony factory in Mexico and pick up the corresponding number of monitors. Then while we're all sleeping, they match up the computers and the monitors, and deliver them to the customer" [142].

The market constraints generated by this type of coordination are present at every level of the system, but are most evident when viewed from the supplier's perspective. One of the primary constraints on every Dell supplier is the timing, quantities, and quality of their component's arrival at Dell final assembly. Too late, or too few of a single suppliers' product, and the entire Dell assembly facility would grind to a halt. Because of this, it is easy to see how these market constraints can *effectively* control the design and manufacturing processes of every Dell supplier. In this way, client organizations—particularly in situations where one company's output is a critical component in another organization's product—can be one of the primary generators of constraints on the design of a product.

Factors arising from existing brand and product management strategies also give rise to market constraints which may affect a design. Product families and technology platforms in which multiple products share common components, manufacturing processes, technologies, or design language often shape an artifact's design. Consider the family of DeWalt cordless power tools. Each tool shares a common design language which tightly constrains the aesthetics of future designs. In order to fit with the larger brand identity, any new DeWalt cordless power tool will almost certainly be molded from exactly the same yellow thermoplastic, with contrasting black design features to help the user understand how to interact with the product. Additionally, the tools are constrained to operate using a previously developed rechargeable lithium ion battery system. The common battery was such an important market constraint, in this case a legacy issue, that when DeWalt released a new line of cordless tools, the homepage of the

DeWalt website directly addressed these concerns. It prominently displayed the text, "Yes, it fits."

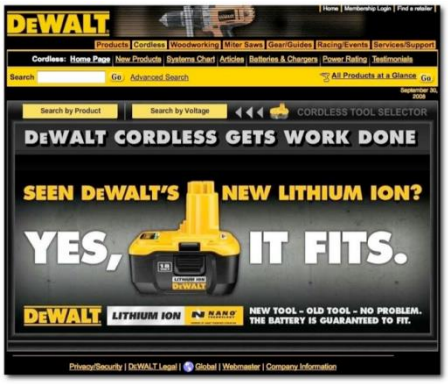


Figure 3.16: The DeWalt homepage addressed an important market constraint after the release of a new lithium ion battery.

While the DeWalt line of power tools represents a very clear case, there are countless other examples in which a company's portfolio architecture—which is "…a strategy for laying out components and systems on multiple products to satisfy market trends" [6]—impacts subsequent products. When a company already owns an existing technology, manufacturing equipment or process, or has designed a cross-functional component, it only makes sense to leverage that in future designs. James Dyson has effectively done this with his line of vacuum cleaners—applying his bagless 'root-cyclone technology' to a range of different vacuum cleaners, from uprights to hand-helds. In a similar way, Proctor and Gamble has leveraged their patented formula for Dawn dish soap—great at cutting grease—within a number of other products ranging from dish washer soap to laundry detergent and stain treatment.

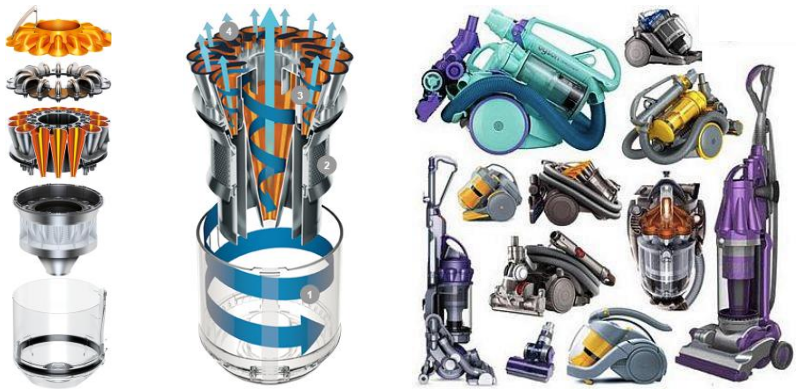


Figure 3.17: Dyson leverages their root-cyclone technology across a variety of vacuum cleaners.

Scalability of the materials, manufacturing processes, and distribution of a product are other market constraints that can be extremely important within commercial design processes. It is one thing to develop a design that performs at the prototype stage or in small-scale production, but when designs are produced in much larger quantities, the design, production methods, and costs must all scale properly in order to maintain viability for the company. Even if a design were to meet every possible user need and provide completely new capabilities, it is unlikely to ever be produced if designers are unable to develop a solution that is financially sustainable at an appropriate market level. While this level will vary from product to product and company to company, the scalability of a design can be of huge importance, and can represent a significant constraint for many industries. Procter & Gamble, for instance, produce and sell their designs in such massive numbers that the scalability of a product and its manufacture is one of the single most important constraints on their design process. To P&G, the development of the next wave of diapers, razors, or cleaning products only holds value if it can be manufactured and sold at massive volumes [143].

This is obviously not true for all industries, as some require much smaller quantities of an artifact than others. Although not strictly speaking a consumer firm, NASA is in many ways constrained by 'market' forces. Because the nature of the enterprise often requires NASA to machine very large, complex components from massive blocks of aluminum, the efficiency of the process is very low, and the cost is astronomically high. On the other extreme, a company like Ball—which manufactures over 50 billion aluminum and steel cans annually [144]—is constrained by the sheer quantity of their product to use the most highly efficient mass

production techniques possible. If either Ball or NASA were to attempt to adopt the fabrication processes of the other—NASA investing in mass production techniques, or Ball trying to machine aluminum cans—their manufacturing techniques would represent an extreme mismatch to the constraints that arise as a result of their particular scale and context. The scale of production demands certain manufacturing processes, which place severe constraints on the design of the artifact itself [6].

Figure 3.18: The constraints on an aluminum can are very different than those on artifacts produced in much smaller quantities.

Regulations are another type of external market constraint that exert a powerful influence over the design process and design solutions. Governmental, industry, and organization wide regulations and standards all affect countless real-world design processes. Regulations are the means by which countries, industries, or organizations establish the standards, practices, and responsibilities to which the member organizations, and in turn their designers, are expected to adhere. These regulations and standards can come in multiple forms: legal regulations imposed by governments, collectively accepted regulations put forth by an industry through a larger collective such as a trade association, or regulations and standards that are proposed and willingly adopted within a single organization.

There are many instances where these market constraints have altered all levels of the artifact system, but emissions standards can be seen as one particularly good example: the United States Congress imposed these legal and governmental regulations and standards through their Corporate Average Fuel Economy (CAFE) regulations in order regulate the CO_2 emissions of passenger vehicles. These standards are currently based upon a vehicle's "footprint," and are set with consideration for technological feasibility, economic practicality, the effect of other fuel economy standards, and the nation's need to conserve energy [145]. These constraints have changed a great deal since their implementation in 1975, and will continue to change into the

foreseeable future [146]. These are the standards to which all vehicles sold in the United States must comply; if they fail to meet such standards, the company responsible is required to pay considerable penalties. As such, the CAFE standards represent a substantial, but somewhat negotiable constraint that is present on the design of every single automobile sold in the United States.

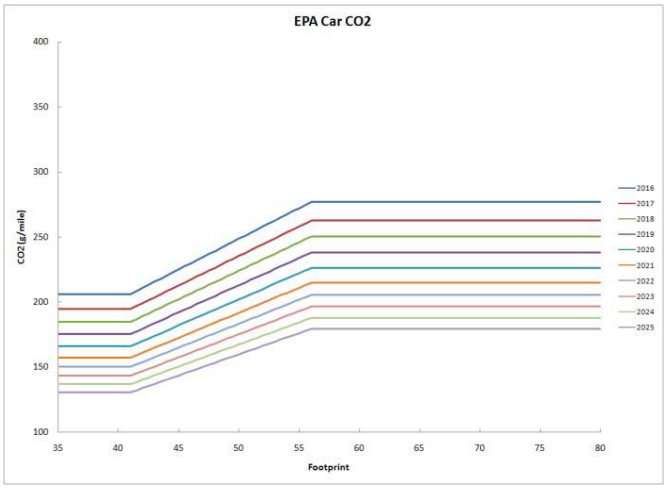


Figure 3.19: The allowable CO2 emissions based upon vehicle footprint have, and will continue to change [147].

Beyond regulations and standards, other legal factors such as patents and proprietary positions also act as a considerable source of constraints for real-world design problems. In many cases, the ability to maintain a proprietary position, or to protect a design through the patent process, is a requirement for proceeding with a project. Conversely, the lack of potential protection or a competitor's patents can be enough to completely stall a project, or at least pose another constraint that designers must factor into a project's budget.

In the case of the modern DSLR camera, some of the most obvious market constraints revolve around how the camera will fit into the firm's extant product portfolio. The price point is typically constrained by the camera's target market (professional vs hobbyist), the rest of the company's current offerings (e.g., is the new DSLR intended as a replacement for a current offering or to fill a currently unmet market segment?), and its likely competition (any new Nikon DSLR must compete with the equivalent Canon offering). Once an approximate price point is determined, it directly constrains many other design decisions, from material choices to the

feasible level of technological sophistication of the camera's sensor. In order to take advantage of research and manufacturing investments, the image sensor technology developed for high–end DSLRs often filters down to the company's point and shoot cameras as newer technologies emerge. For example, Nikon's low-light sensor, initially developed for high end professional DSLRs, has since been applied across a wide variety of their cameras.

In today's market environment, the influence of market constraints on everything from the artifact and the design process to the organization and its associated project management strategies is undeniable. In many ways these factors severely constrain the exploration of the design space, the scope of design projects, and the timing with which they are executed. George Basalla notes the importance of market constraints by saying, "…the freedom to develop technology primarily to serve human needs was lost with the spread of industrialization and the growth of modern megatechnical systems in communications, transportation, power production, and manufacturing…." [82]. While Basalla may be a bit overly deterministic in his statements, there is no denying that market constraints and pressures have the potential to overwhelm many of the other types of constraints. There are countless examples of faulty and less–than–optimal products that were forced out the door too quickly, with designs rendered inadequate as a result of deadlines, reduced costs, and insufficient funding. Even against this backdrop there is still room for change and innovation, but those design changes must work in concert with the market constraints in play for a given situation. Market constraints should not be viewed as a bad thing; nor are they good. Rather, they are merely a dominant fact of life when designing artifacts for complex real-world situations and markets. Given that, it is the task of designers to identify and balance all manner of constraints, from all five of the constraint classes—market constraints included.

3.3.4 Socio-Cultural Constraints

Socio-cultural constraints, as a class, are probably the most difficult type of constraint to identify and differentiate. This is the result of human culture existing as a "pool of information" in the brains of a certain population of people, but only in an aggregate statistical sense. Culture cannot be defined in terms of individuals, and it changes over time based on a very large number of factors [148]. Socio-cultural constraints on artifacts consist of the societal and cultural factors

that shape cognition and behavior, and the ways in which an individual, group, or organization understand and confront designed artifacts. These constraints include factors ranging from how a subset of users approaches a specific task to the preferences and learned behaviors that result from experience, education, religion, or organizational affiliations. This is the area where anthropology, psychology, and sociology can play a crucial role in the product design process, and it requires an appreciation of the role culture plays in the interaction between human populations and design.

Critical to socio-cultural constraints is the recognition that an individual's cognitive processes, with respect to an artifact, are dependent upon factors that go beyond both the artifact and the individual. Every new design an individual encounters is approached and understood within the context of a multitude of previous experiences, understandings, and biases with other artifacts. It is not possible for an adult to approach any new artifact with a completely clean slate, or with an unaffected perspective. Instead, every new artifact is viewed in light of both personal and cultural history and experiences in similar contexts, and with related products. As a result, it is possible to look at socio-cultural constraints as factors that typically exist apart from a firm's design process, as they have been previously learned or ingrained within users.

The concept of culture is, in fact, very much about learning. In their book on the evolutionary nature of cultures, Robert Boyd and Peter J. Richardson define culture as, "…information capable of affecting individuals' behavior that they acquire from other members of their species by teaching, imitation, and other forms of social transmission" [148]. This information, acquired by learning, affects behavior; accordingly, we use words like belief, understanding, value, idea, knowledge, and attitude to describe it. Boyd and Richardson make no mention that this information can be acquired from artifacts, but it is obvious that human–made artifacts are a "source of information" that falls under the banner of "other forms of social transmission." Artifacts, both physical and digital, are social constructs that embody a wealth of information about everything from how a design is to be used, to how the artifact was fabricated, what the state of technology was at the moment of creation, or the worldview of the designer/fabricator. For these reasons, it is appropriate to extend the definition of culture to include learning resulting from information embedded within products.

Socio-cultural constraints arise as the result of previous experiences, learning, training, or education that occurs between individuals, or between individuals and artifacts. This learning is both formal and informal. Formally, these constraints can arise from training or education, as in the case of military training, or training conducted to master a trade. In the case of a military pilot trained on a specific aircraft, this training will affect the way in which he perceives every aircraft subsequently flown. The socio-cultural constraints that arise through experience or education, however, are far broader than this example and stretch across a wide variety of cultures and artifacts. There are most certainly cultures related to all manner of training—whether that is military culture, engineering culture, or the culture of a given manufacturing facility. In fact, it seems that most any field with significantly differentiated education and practice will possess some measure of distinct culture. In each case, this culture shapes its members' perspectives and expectations in ways that will influence their interactions, understandings, and evaluations of every design they encounter. While a group of individuals may possess a shared background, similar experiences, or an equivalent education in an aggregate sense, this does not imply that any two individuals will have identical perspectives, desires, or understandings. These characteristics will frequently be different at the individual level—despite similar histories—but in an aggregate 'cultural sense', these modes of understanding, and the expectations which they produce, often create constraints with regard to everything from the usability of a product to expectations about cost and or perceived reliability.

As an example: in discussions with US Army Rangers regarding the use of physical artifacts in combat, one issue that was re-iterated was a need for absolute reliability—if a product failed once, it would be immediately rejected for future use. The Rangers would simply never bring it into the field again [149]. This mind set makes perfect sense given the very high-risk environment in which Rangers frequently operate, and is not limited to only those individuals who have had an artifact fail in combat. This way of thinking has permeated the entire military culture and is an example of a cultural constraint which has arisen as a result of shared training, experiences, and the demands of combat situations. In a design process focused around combat performance, product reliability takes on another level of importance. Given both the extreme consequences of failure and the need for the artifact to be carried on the back of a foot soldier, the weight given to reliability is extreme. This emphasis on reliability will often give rise to a number of other constraints, both physical and technological, that must be addressed to design

an artifact fit for combat use. All of these constraints can, in some ways, be seen as resulting from this single cultural constraint. This can be seen in contrast to a number of other contexts or "cultures" in which reliability may not carry the same weight.

Socio-cultural constraints certainly arise as the result of education or training, but probably emerge more frequently as a result of informal experiences with products already in the world. No product can exist apart from a user's past experiences. This leads to situations in which users approach new designs with pre-formed ideas, expectations, and desires about how they are to interact with it, and what capabilities it will provide. Every new cellular telephone, for example, is assessed within a framework established by every cellular phone, and probably every phone, that a user has ever interacted with. The reason it is possible to pick up a new cell-phone and nearly immediately begin to use the device is because of previous learning that has occurred with *other* phones. Taken even further, today's smart-phones—part phone, part computer—are understood in the context of constraints established by phones, computers, software programs, etc. Even something as seemingly intuitive as a touch screen smart-phone, is likely to only be immediately intuitive amidst a background of socio-cultural constraints and rules that have been subconsciously ingrained by years of interaction with all manner of electronic devices.

One area where socio–cultural constraints often appear in 'disguise' is in the area of product standardization. Standardization typically occurs as a market constraint when an industry trade group—or perhaps a professional organizations such as the ASME or IEEE—facilitates an agreement across firms to formally agree upon a single standard for some shared aspect of an artifact's design, such as common screw threads or electronic interfaces. In other instances, standardization occurs when a directive is passed down from a governmental or regulatory organization, e.g., a European Union specification for a common power supply (Micro USB) for all mobile devices (phones, tablets, etc.) [150].

In other cases, standardization is a naturally emerging cultural constraint that arises informally through the use and application of multiple designs over many years. In these instances designs tend to converge on a single standard, as the result of the natural benefits to both users and designers. The QWERTY keyboard, drop-down menus in software programs, and the layout of the controls of automobiles are all examples of standards that emerged through constant use, adaptation, and refinement. Over the course of multiple design cycles, design and use become mutually reinforcing: an early design establishes a parameter that is learned by users;

this understanding is then used and perhaps refined by another design team, which further reinforces user's expectations. Eventually, every design team finds itself working with a new constraint that has burrowed its way into the culture of use of that class of device.

In *The Design of Everyday Things*, Norman discusses the standardization of the early automobile that occurred in concert with amelioration of many early technological constraints [18]:

> The first cars were very difficult to operate. They required strength and skill beyond the abilities of many. Some problems were solved through automation: the choke, the spark advance, and the starter engine. Arbitrary aspects of cars and driving had to be standardized: which side of the road people drove on; which side of the car the driver sat on; where the essential components were—steering wheel, brake, clutch, and accelerator… With standardization once you've learned to drive one car, you feel justifiably confident that you can drive any car, anywhere in the world.

Standardization is the formalization of a set of socio-cultural constraints, intended to facilitate understanding, intuitive use, and transferability of knowledge from one product to another. In addition to simplifying usage, Norman also recognizes the negative potential of standardization in that established standards can artificially limit change. One way this occurs is by locking designers into inefficient or inappropriate solutions, technologies, or ways of performing a given task.

Looking at the design of a DSLR, it is tempting to think of cultural constraints as consisting primarily of design features imposed by the consumer cultures of the United States, the European Union, or Japan. It is at least equally likely that the cultural constraints that have the largest impact on the design of high–end cameras emerge from the transnational culture that has grown up around serious photography over the past century. Over many decades, professional and amateur photographers have developed their own 'language', understandings, methods, and approaches for interacting with cameras and related artifacts. As technological constraints reached the point where digital image quality approached that of film, the digital SLR camera was positioned to represent, for many photographers, their first foray into the new digital medium. Accordingly, digital cameras were constrained to operate with respect to the cultural constraints that had developed over years of shooting film: snapping a picture, changing lenses, and adjusting exposure settings all needed to fit within the film shooter's mental models and understandings of how to operate and interact with a serious, high–end camera.

These constraints are seen most clearly when one realizes that digital SLR cameras, despite the fact that they no longer rely on 35mm film, continue to look, feel, and operate quite similarly to film–based SLRs. For no functional reason, physical features such as the film-winder and the shape and form of the camera live on, even though they have been repurposed and re-imagined for digital operation. In fact, one complaint about DSLR cameras has been that moving to digital controls has complicated the photographer's interaction whilst looking through the camera.

Changing the aperture, in particular, is a good example of this problem. Before the advent of digital camera controls, changing the aperture was a mechanical operation carried out by turning a ring on the lens itself. This was an intuitive mapping of function to control, and easily allowed photographers to adjust aperture whilst looking through the camera. As digital controls became more pervasive, this mapping became more complex, and the aperture could no longer be controlled on the lens. Instead, aperture now had to be controlled using dials on the camera body—sometimes in conjunction with other button presses intended to specify the function currently controlled by the dial (as in the case where a single dial adjusts both shutter speed and aperture). These changes, however, worked contrary to the desired and customary operation of an SLR camera that had been ingrained, over time, within the minds of photographers around the world. These socio-cultural constraints—obviously tied to use, and initially ignored by camera designers and manufacturers—have since been recognized. In fact, some manufacturers have begun designing cameras and lenses that once again allow the aperture to be controlled on the barrel of the lens—in a manner similar to the old-style SLR cameras and lenses. While there are certainly other factors that have contributed to the re-introduction of these modes of operation, the influence of the constraints arising from the user culture of serious photography is evident.

Cultural constraints also frequently arise from individuals and stakeholders who are not typically seen as end-users. While this might seem counter–intuitive, cultural constraints can arise from *any* stakeholder within the product system. As noted above, cultural constraints quite often give rise to constraints of use—as in the cases of serious photographers or the Army Rangers. But constraints can arise from other perspectives within a culture, such as designers and manufacturers, so we must be explicit when defining 'culture'. While it certainly represents factors like the culture of a country, or human culture, it may also represent a wide range of

groups at multiple scales, e.g., corporate cultures, organizational cultures, and industry cultures. Very often multiple 'cultures' are represented in the design and use of any particular object. Accordingly, designers are tasked to navigate socio-cultural constraints that arise from users, manufacturers, and clients, as well as the socio-cultural constraints that shape their own perspectives.

The design of the cup-holder in the Mercedes E350 can be seen as an illustrative example of the designer's need to understand and balance socio-cultural constraints that arise from their own personal experiences. For a vehicle and interior with very high standards of design and polish, the cup holder in this particular vehicle seems decidedly slapdash—almost as if it were thrown in at the last minute with little consideration for how it would interact with the passengers or the rest of the car's interior. It is not that the cup holder is aesthetically unpleasing, or that it is unable to adequately perform its intended function of holding a beverage. Rather, this cup holder seems to be designed to intentionally discourage use while driving. The cup holder is placed almost directly behind the gear shift knob, such that the driver's elbow will dislodge and knock over any beverage that is placed in the cup holder for safe keeping [151]. This is certainly a problem with the straight pattern automatic transmission, but even more so for models with a manual transmission—with the driver's elbow even more frequently needing to occupy the same space as the beverage. One might wonder how a conflict so glaring managed to slide past some of the best engineers and designers at Mercedes.

Figure 3.20: The seemingly odd placement of the cupholder in the Mercedes E350.

It is likely that this problem arose as the result of unrecognized cultural constraints. The E350 was designed in Germany, where the thought of drinking a coffee during one's morning commute is almost unheard of. In America however—where Mercedes sells a significant number of vehicles—a coffee during the morning commute has become something of a morning ritual. Drinking coffee while driving, so important to many Americans, is seen as unnecessary and dangerous in the culture in which the vehicle originated. According to *Motor Trend*, "…a Mercedes-Benz engineer once explained to me how the German [car] owner is very different from his counterparts around the world. In Germany everything regarding automobiles (and beer and sausage making for that matter) is taken very seriously. You need only look at autobahn lane discipline and how many months and Euros it takes to get a German driver's license as evidence." [152]. Thus it's likely that the cup-holder *was* added to the vehicle as an afterthought—just one more requirement of selling to the American market. In actuality, the design of the cup holder needed to address not only a market constraint, but an important usage constraint as well. A lack of understanding, or even recognizing, this cultural constraint on the part of the Mercedes engineers ultimately led to the design of a cup-holder that met its functional requirements, narrowly defined, but failed to achieve the desired goals of the user.

One might assume that this particular vehicle is an anomaly, chosen as an unrepresentative sample in order to illustrate a point, but similar complaints have been levied against a wide variety of European designed vehicles. In fact, there are a number of aftermarket products designed solely with the purpose of better accommodating Americans' habit of travelling with beverages. One product in particular—the *Ultimate Cupholder*, which is specifically designed for use in BMWs, Mercedes, Audis, and Porches—is marketed as "…a practical cup holder designed for the real world by an owner who actually drives the cars and uses the holders" [153]. This product is indicative of the large number of issues that can arise as the result of socio-cultural constraints—both considered and unrecognized.

Figure 3.21: The Ultimate Cupholder is a user-designed product intended to address issues that resulted from cultural constraints.

While socio-cultural constraints encompass a wide variety of factors relevant to the design, adoption, and use of artifacts, one sub-category that deserves particular attention is aesthetics. The importance of aesthetics in product design is beyond dispute, but at the same time the actual value of a product's aesthetics can be quite difficult to quantify. While certainly not limited to aesthetics, some fields of design—industrial design and architecture, in particular—give extensive time and effort to training practitioners in the design and implementation of aesthetic choices. Karl T. Ulrich of the Wharton School defines aesthetics as:

> The aesthetics of an artifact are the immediate feelings evoked when experiencing that artifact via the sensory system. I consider aesthetic responses to be different from other cognitive responses in at least three ways. Aesthetic response is rapid, usually within seconds of exposure to the artifact. Aesthetic response is involuntary, requiring little if any expenditure of cognitive effort. Aesthetic response is an aggregate assessment biased either positively (e.g., beauty or attraction) or negatively (e.g., ugliness or repulsion) and not a nuanced multi-dimensional evaluation.

This response is most frequently associated with visual information. Users' judgments about beauty, elegance, or aesthetic satisfaction are based in cognitive mechanisms, and represent an important piece of the evaluation of a design. Despite the fact that aesthetics *can* be separated from functionality, humans prefer aesthetically pleasing products—particularly if all other factors are held equal. This seems to hold true not just for consumer products, but for other highly functional domains as well. According to an engineer who designs military hardware, when showing soldiers a prototype of a piece of military hardware, one of the most frequent questions is, 'Does it come in black?' – which turns out to be the most widely held

preference, both because of its non-reflectivity and its aesthetic appeal within American military culture [154].

Aesthetics is clearly a key factor in providing a positive user experience, and stands alongside other product attributes like cost, durability, and ease of use for the purposes of evaluation. The aesthetics of a design lead to an unavoidable first impression, which may be positive or negative, and also seem to communicate to the user "…unobservable attributes of quality." Beauty or the well-designed form of an object seems to infer underlying quality, whereas objects seen as non–pleasing from an aesthetic standpoint may be regarded as having inferior quality. In every case, individuals' responses to the visual stimuli of designed artifacts are cognitive judgments that are learned through experiences with previous artifacts or as the result of societal factors. Because of this, aesthetic judgments "…differ widely across times and across cultures." [155]. This can be easily seen in the changing appearance of functionally similar designs over time. Since the introduction of the first pop-up toaster in 1919 (Waters Genter Company's Toastmaster 1-A-1), for example, the aesthetic design of toasters has changed considerably despite the underlying technology remaining relatively static [156]. Looking at the evolution of toasters through the years, one sees a variety of styles, but also a basic shape that has been retained—as a result of the need to hold and brown both sides of a piece of toast, the toaster's primary function.

Figure 3.22: The appearances of toasters have changed considerably since the introduction of the Toastmaster 1-A-1 (top left).

While aesthetic preferences are frequently the result of societal and cultural factors, any genuine discussion of aesthetics must address the tension between individual and collective preference. Just as with all socio-cultural factors, it is only possible to talk about aesthetics in an aggregate sense, as individuals will inevitably disagree about the aesthetic value of any single artifact. For example, it is quite possible that you and I would disagree about the attractiveness of the Black and Decker MGD100 toaster designed for Target stores by Michael Graves (bottom row, third from left). It is even reasonable to assume that between two similarly raised, educated, and experienced individuals there will be differing reactions to a product's form, ranging from awe-struck reverence to utter disdain. For the designer, it is not possible to design to the unique tastes of every single individual. Instead, the focus becomes designing a product's aesthetics in such a way as to support the overall design intent and to appeal to as many potential users as possible, which is why aesthetics lies within the class of socio-cultural constraints.

On occasion, it is possible that the aesthetics of physical goods can dominate user preference, particularly when all of the artifacts within a market meet the same level of functional requirements. Taken to extremes, this can be seen in the seasonal trends and fashions that appear in certain product segments, most notably clothing. As most clothing fulfills the functional requirements of covering the body and providing an appropriate level of warmth, designers turn their attention towards aesthetics in order to differentiate their products. Each season, clothing designers re-invent their aesthetics in order to appeal to consumers while differentiating themselves from both their competitors and their own previous designs. While clothing is an extreme example of this, similar practices frequently occur in the realm of consumer products as well. Vehicles, for instance, are typically released every model year with updated aesthetics, whether there have been functional changes to the rest of the vehicle or not.

Regardless of the market segment, aesthetics proves that socio-cultural constraints can change quite rapidly. It is also clear that cultural constraints may change alongside other constraint categories—most frequently technological, market, and use constraints. A new technology can shape cultural expectations, and in turn those cultural expectations shape future products and usage. One example of this can be drawn from many individuals' experiences using, or more appropriately misusing, the touch screen interfaces that are becoming more and more prevalent in today's world. With the introduction of touch screen computers, tablets, phones, and displays, a new mode of interaction has been established through which a user can

manipulate information simply by touching the display surface. As a result, there is now a tendency for this learned behavior to be incorrectly transferred to non-touch screen displays, and users frequently find themselves tapping or swiping flat screen displays and devices to no avail, as none of these are behaviors supported by the products themselves.

Because objects are interpreted within a framework established by other similar technologies, users often misuse products by performing actions that were unintended and unsupported by designers. The misappropriation of this learning is not unique to any single individual; instead, this is a cultural problem that broadly affects the users of these designs. Existing artifacts set expectations for evaluation and use that become ingrained within the surrounding culture, shaping the way users approach and understand every new object that they encounter. This does not mean that every screen-based device should be designed with touch-screen interactivity, but rather that designers must be aware of the learned affordances ingrained within a culture. It is the role of designers to recognize, anticipate, and design within the framework established by these socio-cultural constraints.

Returning to a more broad view, there is sometimes a tendency for socio-cultural constraints to be viewed as 'soft' constraints, as they are frequently more difficult to quantify. Allowing their at times imprecise nature to diminish their importance within the design process, however, can be a costly error. Therefore, it is critical that designers attempt to understand the effects of socio-cultural constraints on a product's implementation and use, as well as on their own thinking. Whether defining culture broadly—as in the case of countries and people groups—or much more narrowly—as in the case of a singular artifact culture—existing artifacts predispose individuals and organizations to certain expectations, desires, and evaluation criteria. In the design and manufacture of almost any object, designers will confront the culture of the designing organization, the culture of the client organization, the culture of the manufacturing floor which must produce and assemble the design, as well as the multiple subcultures that will ultimately use the design. These cultures give rise to the socio-cultural constraints that are present on almost every artifact, and can have an impact on its adoption, use, success, and failure.

3.3.5 Constraints of Use

Like socio-cultural constraints, constraints of use appear when the system of interest is defined to include more than just the artifact; they emerge as a result of interactions between the user, the artifact itself, and the context in which it's used, i.e., the larger unit of design. Usage constraints are typically concerned with ergonomic and human factors issues, as they pertain to the interaction of the human user and the artifact. The task in which a user is engaged, along with their understanding of that task and the context are all important elements that have some bearing on how the artifact will be used. Each of these results in constraints of use that affect the performance of the design. Beyond those factors, the goals, desires, and emotions of users also have a bearing on how an artifact is viewed and used within a field of activity. Usage constraints often address, or arise as the result of, questions such as: what functionality and capabilities does the user need, expect, and desire? What information does the user need for a given situation or task? When do they need it? And, what form do they need it in so that the information can be used to achieve their goal?

These are just a few of the questions that are typically asked by human factors specialists and ergonomists, but they are central to the practice of design, whether they are explicitly recognized or not. Every design embodies decisions about how to address the uncertainty in the interactions that will exist between artifacts and users, within a particular context. While it is feasible to view and design an artifact in isolation from these factors, it will most likely lead to difficulties for the user once the artifact is released into the world. As Simon notes, this is because *every* artifact is embedded within a "human system," as all artifacts exist in order to meet human goals and purposes. Every single design is created in order to provide value or achieve a purpose that exists beyond the artifact itself [38]. Thus constraints of use are pervasive regardless of the design context, or its perceived isolation from human involvement. Even a seemingly remote component, nestled within the reactor of a nuclear power plant, for example, was manufactured by someone, installed and maintained by someone else, and understood—in terms of its function, interaction with other parts, and how it might fail—by the operators. It also exists as one component of a larger system, which is responsible for providing power to hundreds of thousands of individuals, and jobs to thousands more. While it is often convenient to ignore the impacts an artifact can have on all of the "users" it comes into contact with, doing so is decidedly unwise.

Usage constraints are always focused on the people who, in one form or another, interact with a designed artifact. While it might be easiest to think about constraints of use in the context of the consumer end–user, these constraints affect numerous other stakeholders as well. "Use" and "users" shift dramatically as an artifact progresses through its life cycle. Certainly a large number—possibly even the majority—of usage constraints emerge at the intersection of the artifact and the end-user, but it is important to also recognize the other generators of usage constraints within the system. During an artifact's production, for example, the individuals responsible for an artifact's manufacture and assembly can also be seen as "users," and there are a number of constraints that must be balanced within a design in order to facilitate proper interaction between production personnel and the artifact. In many ways, design strategies such as Design for Manufacture (DFM) and Design for Assembly (DFA) manage usage constraints from the perspective of manufacturing and assembly personnel. Similarly, it is possible to focus on the interaction of the artifact and service/maintenance personnel, distribution and retail personnel, and those responsible for disassembly, recycling, and/or remanufacture [2]. As the artifact moves from initial design to real object, it gives rise at each stage to usage constraints that may be critical to the performance or success of a designed artifact.

Constraints of use are a major reason why design teams draw from many disciplines, including anthropometry, bio-mechanics, kinesiology, industrial engineering, mechanical engineering, and psychology. In every case, the focus is on the interaction between the user and the artifact within some particular context. Whether focused on the physical aspects of an artifact (such as its size and shape) or its cognitive properties (how it presented, understood, and accessed), the relationship between the artifact and the user is central to every usage constraint. As noted earlier, there are a number of fields which claim these constraints as their reason for being: human factors, physical ergonomics, cognitive ergonomics, usability engineering, and user-centered design, just to name a few. In reality, constraints of use touch upon the domain of every designer—engineers, ergonomists, and industrial designers alike—and as such, it is crucial that these disciplines are represented.

Ergonomists, in particular, have made explicit the relationship between the user and the artifact, defining ergonomics as, "…the study of the interaction between people and machines and the factors that affect that interaction…", with particular attention paid to the "…design of the interface between the two." Ergonomics is concerned with the compatibility between the

user and the rest of the system at a number of levels including, "…biomechanical, anatomical, physiological, behavioral, and cognitive levels…." [157]. But whether physical or cognitive aspects of these principles apply, the interface between user and artifact is almost always embodied within the artifact, and is therefore the responsibility of the designer. Designers, intentionally or not, define the physical and cognitive interfaces between users and products, artifacts, and systems.

Physical ergonomics deals primarily with how well humans and designed artifacts fit together physically. As the name suggests, the constraints falling under the category of physical ergonomics are often closely coupled with physical constraints relating to their implementation. Principles of physical ergonomics are used frequently in the design of both consumer products and industrial settings. In consumer products, the focus is most often on improving the physical interface between the end-user and the artifact. Examples of physical ergonomics include: the grip on an electric drill and the manner in which it conforms to the hand, directs posture, transfers force, and reduces vibration; the key size, layout, and tactile feedback of a smart-phone keypad, and the way in which those factors interact with the human hand, dexterity, and range of motion; or the chair your back is 'interacting' with right now. In industrial settings, the primary concern of physical ergonomics is most often the interaction of the manufacturing personnel and the work environment. The focus is frequently on the reduction and elimination of repetitive stress injuries that result from constantly repeated postures, motions, and interactions. In an attempt to reduce work-related injuries ergonomists frequently focus on workstation redesign, employee training, task redesign, and the introduction of new tools to reduce the risk to workers. But it is also important to recognize the role that the designed artifact plays in manufacturing and assembly, as the assembly process and workspace layout are implied and established by the artifact's structure.

The design of an artifact, established long before it is produced, dictates many aspects of the product's manufacture and assembly. For example, the structure of a design's components establishes the order of assembly, the number of pre-assembled modules that can be used, and the orientation of the parts during the assembly process. This, in turn, establishes the number of steps that must be performed during assembly, the ease or difficulty of workers' tasks, and the speed at which an assembly task can be performed. Knowingly or not, designers specify the

physical interactions between an artifact and all of its users—from assembly personnel to consumers.

If the primary focus of physical ergonomics is the way in which an artifact and its users physically interface with one another, then it logically follows that cognitive ergonomics places an emphasis on understanding and specifying the ways in which humans and artifacts interact cognitively. It is not concerned with physical modes of interaction, but rather the cognitive processes engaged in by the artifact's users. The user's assessment and understanding of an artifact, in addition to their decision making and planning with respect to the use context, are the chief concerns of cognitive ergonomics. By understanding the usage constraints that arise as the result of these cognitive factors, it is possible to enhance the user's cognitive performance as it relates to the artifact, and any tasks performed in concert with that artifact. Just as with physical ergonomics, the locus of cognitive interaction between a user and an artifact is embodied within the artifact itself. The way in which a user will interact with, and understand, a design is prescribed by the artifact, which places a large burden on the designer to anticipate and structure the interaction between user and artifact. In many ways, the design determines the nature of the task by imposing constraints on what is possible and how the interaction will occur.

Because the artifact is so closely tied to the purposes for which it is used, developing a thorough understanding of the relevant cognitive factors requires an understanding of not only the user and the artifact, but also the context in which user and artifact are embedded. In fact, it is likely that these cognitive constraints only truly emerge at the intersection of the user, the design, and the activity [17], [24], [44]. These cognitive usage constraints have always been important, but in today's world of software, digital products, and complex systems, their influence and importance is only growing. As products and systems become increasingly sophisticated, the importance of designing for cognitive constraints is amplified, as these aspects of an artifact's design often dominate the way in which a user understands a design. Along those lines, as objects become more and more software dependent, there is an increased emphasis on the controls, through which an individual interfaces with a design. This has given rise to the fields of interaction design, user-interface design, and human-computer interaction (HCI). These fields address users' interactions with digital artifacts, environments, or systems, based upon investigation of users' goals, understandings, strategies, and behaviors [158].

In many ways, HCI, interaction design, and the associated cognitive aspects of design are fast becoming the principal usage constraints of the digital age. But the principles derived from these cognitive aspects of design are not expressly limited to graphical user interfaces, software, or digital products. Instead, these cognitive issues and constraints are an inseparable part of every type of design, because the designs themselves cannot be separated from the human systems in which they exist. Because all artifacts are designed to assist people in achieving some goal or purpose, "…their design, as well as their evaluation, inherently and inextricably involve psychological issues." [17].

In his well-respected work on user-centered design, *The Psychology of Everyday Things* (later published as *The Design of Everyday Things*), Norman explores the role cognition plays within individuals' interactions with everyday objects and products [18]. While built on a foundation of psychological principles like memory, attention, learning, and mental models, this book is still fundamentally about design. Through a number of case studies—most famously hard to open doors and confusing shower controls—Norman explores the importance of design, and the consequences of bad designs that do not fit with how people actually think. Focusing on user cognition, Norman also puts forth a number of principles which have shaped user-centered design, and the way people analyze products. These principles include using information in the user's mind and the context, simplifying the structure of tasks, making things visible, getting the mapping right, directing users by constraining possible actions, designing for error, and standardization.

While these principles are valuable, they do not fully cover all of the usage constraints related to cognition. It is important to recognize that factors such as a user's emotions, feelings, and desires can also exert a powerful influence on the way in which individuals approach, understand, and use designed artifacts. This is something Norman ultimately recognized and addressed in his book, *Emotional Design: Why We Love (or Hate) Everyday Things* [159]. Since then, the concept of "emotional experience" and its role in design practice, research, and industry has only grown [160]. The Design and Emotion Society has hosted a Design and Emotion Conference since 1999, and the emotional experience of users has played a key role in enriching everything from Alessi home-goods [66] to experience design (the process of "using" a hospital or airport, for instance) [161], [162]. Between physical, cognitive, and emotional issues, none stand apart. Instead, each represents an important subset of usage constraints that, when taken

as a whole, strongly influence the way in which designed artifacts perform once introduced into the context of use.

Figure 3.23: Italian company, Alessi, has long been known for their fun products that seek to generate an emotional response.

Returning to the example of the digital camera, there are many instances in which the design of a digital SLR is influenced by constraints of use. Constraints arising from both cognitive and physical ergonomics are featured prominently, as a digital SLR relies on both software (digital) and hardware (physical) interfaces across a number of functions. Initially, decisions regarding the mapping of functions to controls (both software and hardware) are a primary concern, as designers are forced to address which camera controls need to be adjustable on the body of the camera, and which are to be accessed through a menu. These decisions are made with respect to usage constraints that pertain to the photographer's mental model of how the camera operates, the ability to quickly and adequately locate controls (sometimes within menus), and the ability of the photographer to interact with the physical dials and buttons.

All of these decisions are made more complicated, however, when this interaction is situated within the context and immediate goals of the photographer. Navigation and interaction exist in order to help the photographer capture a desired image, which often means that these settings must be controllable while looking through the lens, rather than at the camera, and must be available at the exact moment the photographer needs them—otherwise, the desired shot is missed. While this most notably affects the placement and design of aperture, focus, and shutter speed controls, every aspect of the camera must defer to the photographer's goal of capturing the perfect image. In this way every aspect of the camera's design is constrained by design decisions regarding use.

Physical constraints on the weight, size, and feel of a camera are also very important. This applies to ensuring proper hand placement (with respect to the shutter and the controls), correctly balancing the camera's weight (in order to stabilize the camera), and the material and surface finishes that specify the way the camera feels in the hands of the photographer. The feel, in particular, has the ability to elicit an emotional response from the user, and subconsciously convey ideas about the camera's quality and value. These sorts of constraints are often harder to pin down, but every product designer knows that artifacts elicit these types of feelings from users. We have all experienced this sensation first hand when picking up an object that just "feels" solid. Finely constructed, pleasurable, and well designed—it just feels right. While this may seem natural, begging the question, "…why would it be any other way?" [163], it is the result of a great deal of effort by designers to identify and balance a myriad of constraints relating to the artifact's usage.

While designers spend an immeasurable amount of time identifying and addressing usage constraints, it is not possible for designers to anticipate and address every possible constraint for every user. There always will be a set of constraints that remain unaddressed for at least some segment of the user population. Additionally, there are constraints that only emerge after the design has been introduced. These unaddressed and emergent usage constraints are often addressed by individual users themselves. In order to address these unforeseen constraints, small segments of the user population augment existing designs and develop their own solutions using their ingenuity, experience, and expertise. All this in order to adapt existing artifacts into forms that are more usable, more applicable, and more fit for their particular goals and desires—that is, more aligned to their own specific, and very current, set of constraints.

MIT's Erik Von Hippel has published research on highly knowledgeable "lead users" who develop innovative advances to existing technologies. The reason that this is possible, he argues, is that users have information about their own needs and contexts that is typically not available to design organizations. His accounts of these innovations range from sporting goods to software and high-tech machinery [102]. Essentially, these individuals have a more accurate picture of their own usage constraints, and are therefore able to frame the design problem and envision solutions not possible from the perspective of designers. This sort of behavior, however, extends well beyond lead users. Users of all types and levels of expertise are, according to IDEO's Jane Fulton Suri, "…never quite satisfied with the things that they have" [164].

Whether modifying an existing design or just attaching post-it notes to a product in order to act as a memory aid, these changes are all intended to address new, or unsatisfactorily addressed, usage constraints. These sorts of adaptations happen for every class of product, in every context, and in every region of the world.

Kevin Kelly—founding executive editor of Wired magazine—runs a blog called Street Use, in which he collects examples of products adapted and re-invented by individuals who are in some way dissatisfied with a product in its 'as designed' state. He eloquently introduces his blog [165]:

> This site features the ways in which people modify and re-create technology. Herein a collection of personal modifications, folk innovations, street customization, ad hoc alterations, wear-patterns, home-made versions and indigenous ingenuity. In short—stuff as it is actually used, and not how its creators planned on it being used. As William Gibson said, "The street finds its own uses for things."

Jan Chipchase, currently the Executive Creative Director at the global design and innovation consultancy 'frog,' has a similar blog called Future Perfect. In it, Chipchase—who has spent his career researching the intersection of technology and use in cultures all around the world—posts hacks, modifications, and design inspiration from all over the world. These blogs feature examples of adaptation from prisons, foreign markets, and, most prominently, developing countries. The examples from developing countries are likely so numerous, as the result of these individuals using products not specifically designed for them. Because these individuals are using products designed for others, their needs, goals, and capabilities represent an un-identified, un-explored, and un-designed–for set of usage constraints. The solutions generated represent some astounding examples of creativity drawn out by necessity.

Figure 3.24: Two examples of street hacks: a twenty year old Sony calculator wrapped in a carpenter made casing, and a Vice-Grip with a pipe elbow welded to it to act as a palm rest and allow one handed operation.

As is evident from these examples, usage constraints are often closely coupled with socio-cultural constraints, as well. Pre-existing socio-cultural factors frequently shape the way in which users approach, understand, and interact with artifacts. Past training, education, and experiences all affect an artifact's usage. In fact, every design is evaluated and used within the context of previously learned socio-cultural information, tendencies, biases, and understandings, often resulting from interactions and experiences with previous artifacts. As we have seen, our cultural understanding of how to use and interact with cellular phones, learned over years of use, is subconsciously applied to every new phone that we pick up. Taking this example one step further, cultural factors impact not only how the artifact is used and interacted with, but also users' expectations for what the artifact will do. That is, what role it will play in their lives, the functions it will perform, the goals and needs it will allow them to fulfill, and the capabilities it will afford them in a given context. In this way, socio-cultural constraints shape individuals' expectations of usage, and usage in turn shapes future cultural constraints. As cellular phones shifted into personal organizers, and then into cameras, web-browsers, gaming devices, and portable computing systems, users' expectations shifted as well. This growing list of features (enabled by technological progress) characterizes users' redefined expectations about the capabilities that cellular devices can—and in some senses, must—provide in their lives. By better allowing users to manage communication, work, and entertainment, these capabilities have shifted what a mobile phone is, and the role that these devices play within our lives and cultures.

In combination, socio-cultural and usage constraints embody many of the fine details that drive the assimilation and use of all designed artifacts. Cognitive factors such as knowledge, goals, and emotions shape the way in which individuals approach, use, and evaluate designs. When combined with the physical and cognitive interfaces implemented by designers, these

constraints determine the experiential qualities of an artifact. While socio-cultural and usage constraints can certainly be more qualitative or abstract than their physical, technological, and market counterparts, they are no less important. In fact, they are at the heart of designing successful artifacts.

3.4 Properties of Constraints

3.4.1 Intrinsic and Extrinsic

The five classes of constraints previously outlined are, at their core, intended to provide a framework through which designers can better explore, manage, and communicate with regard to the multitude of constraints and opportunities that are present within every real-world design process. Their utility lies primarily in the structure that these constraint categories can provide when analyzing and exploring complex artifact systems, as the constraint framework allows designers to make explicit the factors, relationships, and structures that drive the *true* performance of an artifact system.

At the same time, this is not a prescriptive design model, nor is it an explicit process which, upon completion, will yield design solutions. It is a structure intended to facilitate understanding and productive thought, by allowing designers to make explicit the constraints and opportunities that drive their processes. With that in mind, we must again recognize that these five categories of constraints are intended to cover as wide a range of design scenarios as possible, and as such they may be less than ideally specified for a specific design task or process. Moreover, it is unlikely that every single constraint will fit neatly into these five categories, and specific constraints may frequently be embodied in, and tied to, multiple classes of constraints. This is most often the result of the high levels of interaction that exist between the categories of constraints.

There are clearly other types, and sub-classes, of constraints that exert an influence on product design and performance. As discussed, however, I claim that these constraints can be constructed and explained as combinations, or derivatives, of the five general categories highlighted here. For example, aesthetic constraints—despite their inclusion within the socio-cultural constraints—are typically driven by some combination of socio-cultural, market, and physical factors. Similarly, performance constraints are typically defined by some combination of

physical, technological, market, and usage constraints. Thus, these five categories of constraints are not an all–encompassing and universally applicable list of every constraint that influences artifact design and performance. They are, however, one suitable approximation of the *most basic* set of constraints that can be defined and used to construct and explain the constraints that engineers and industrial designers routinely encounter. In a way, they are a set of building blocks from which every design situation can be constructed and explained. The categories are not perfect, but they do not need to be in order to provide structure and value.

In looking at the five categories of constraints, it is beneficial to further explore their structure. These five categories lend themselves to being sub-divided into two large classes [111]: *intrinsic constraints* that apply to the artifact itself, and *extrinsic constraints* that exist only at the system level. The word intrinsic refers to some aspect, or property, "of or relating to the essential nature of a thing." It is derived from the Latin *intresecus*, which means "from within" [166]. As such, intrinsic constraints are those which arise from within the design and apply to the artifact itself, without any consideration given to any particular user, stakeholder, or context. These intrinsic constraints may arise as a result of single component, or a collection of components—as in the case of an entire artifact [90]. Typically, these constraints relate to what a component or artifact can or cannot do, or the fundamental properties that drive its operation—as in the case of material properties or Newtonian physics.

Extrinsic constraints, on the other hand, are system-level constraints that arise as the result of the interactions of the entire artifact system, rather than as a result of any single component. These are constraints that only result from the interaction of the artifact and the user, market, culture, or context. The word extrinsic means "originating or acting from outside" [167], and is used in biology to connote a structure, frequently a muscle, "originating outside of the part where it is found or upon which it acts" [168]. The six muscles, which move and control the human eye, for example, are extrinsic muscles—in that they exist apart from the eye itself. In the same way, the extrinsic constraints affect an artifact's use and performance despite their origin apart from the artifact itself—they only manifest themselves when an artifact is encountered by a specific person in a specific real-world context. In practice, the importance of these extrinsic constraints is what drives design organizations to conduct user research, develop personas and scenarios, and engage in market research and comparative benchmarking. Each helps the organization to uncover important extrinsic constraints when designing new artifacts.

Extrinsic constraints require designers to broaden their view of the artifact and the process, as they only become apparent when an artifact is viewed through the lens of the larger unit of design.

While the distinction of whether constraints arise from within or from without is a meaningful one, the real value is in understanding how designers must understand and address these constraints. Intrinsic constraints can generally be identified, addressed, and managed directly by designers. A physical artifact's weight, size, durability and performance can be designed, tracked, and adjusted directly prior to an artifact's introduction. Extrinsic constraints, conversely, must be anticipated by designers, as they only exist as part of the larger unit of design. At the same time, this anticipation of extrinsic constraints is based upon imperfect information and limited understanding—recall that every design is, at some level, a hypothesis. As extrinsic constraints are embodied in a larger artifact system that does not yet exist (at least not with the new artifact as a component part), they can typically only be addressed indirectly. While the domain of the designer is the entire larger unit of design, the only piece of the system that the designer can directly address is the artifact itself. The designer affects change in the system by altering the artifact—not the user or the context, which can only be affected indirectly.

Looking back to the five categories of constraints, technological and physical constraints can be both intrinsic or extrinsic—in the case of the DSLR camera, for example, the constraint that the camera body has to be light-tight is inherent to the functioning of the artifact itself. The size and weight, however, are constraints that are contingent on the interaction of the camera and its user. Conversely, usage and socio-cultural constraints are, by their very nature, extrinsic; they exist as a part of the larger system that includes the artifact, the user, and the context. While it is possible to make the argument that market constraints exist only as extrinsic constraints, it seems more likely that, like physical and technological constraints, they can exist both intrinsically and extrinsically.

In the introduction to this chapter, I suggested that it is possible to view the constraint categories on a continuum that ranges from concrete to abstract—with physical and technological constraints tending to be more concrete than market constraints, which tend to be more concrete than usage and socio-cultural constraints. It is now possible to see that this is likely the result of physical and technological constraints being more likely to be intrinsic—inherent to the artifact itself—while the usage and socio-cultural constraints are extrinsic,

existing only as a part of the larger artifact system. Accordingly, it is often a much more straightforward process for designers to track and address the physical and technological constraints on an artifact than it is to anticipate and design for extrinsic usage and socio-cultural constraints that only emerge at the intersection of the artifact, user, and context.

3.4.2 Closeness, Control, and the Weight of Constraints

In *How Designers Work: Making sense of authentic cognitive activity*, Henryk Gedenryd questions the role and value of constraints in the design process [55]: "Is a constraint helpful or a hindrance, is it fixed or optional, is it provided in advance or added during design, and is it given to the designer, in the problem definition, or imposed by the designer, entirely at her own discretion?" Constraints can be all of these things, and they can be none of these things—they are inherent to the process and imposed by designers, they provide necessary structure and define nebulous challenges; they can be both a boon and a bane.

If constraints can represent both problems and opportunities, and can be embodied in the solution (the design itself) or the formulation of the design problem (the encompassing context), how are designers to gain value from constraints despite their amorphous nature? In presenting such a view of constraints, one must confront the value of the constraint framework within the design process, as there is no sense in complicating matters if it does not confer significant benefits. Viewed another way, the struggles associated with making sense of a constraint framework can be seen as a positive, as they are indicative of a more authentic picture of design activity within a complex world. If the categorization of constraints was simple, clear-cut, and singular there would be no way that they could accurately capture the messiness and uncertainty of design processes and complex artifact systems. Instead, this more nuanced view of constraints more closely emulates the complexity of real world artifact design and implementation: the complexity of the design space is reflected in the complexity of the constraints with which we attempt to characterize it. The value of constraints lies in their ability to help designers deal with the complexity inherent in every real-world artifact system, but this is only possible if we understand how constraints are actually leveraged within the design process.

We have already recognized that the set of constraints for a particular problem is not fixed, and that designers have some amount of control over which constraints they choose to

address. As a result, each designer and organization may choose to focus on a different set of constraints. The constraints on a design problem are understood and prioritized differently by every designer and organization, and it is in these differences that we can better understand their role within the design process [55]. Accordingly, the discussion of constraints must be characterized by a flexible and changing constraint set, which is dependent upon how individual designers choose to deal with these constraints within a design process.

Designers impose constraints in order provide structure to the design space, reduce ambiguity, and direct design. Accordingly, constraints are only meaningful when designers are able to exert some level of control over the constraints themselves, and the degree to which constraints are controllable by the designer is critical to their value. Certain constraints can be changed, applied, and removed in order to explore and provide structure, while others are more difficult to change. Looking at constraints, there appears to be a relationship between the source of a constraint and its degree of negotiability: the constraints that are fundamental to the nature of the problem are frequently non-negotiable, and are almost always less negotiable than imposed constraints. But even within the set of constraints imposed by governments, organizations, clients, and designers, there are obvious differences in the degree to which a constraint can be affected. In many ways, this distinction can be seen in the difference between requirements imposed by a client and goals imposed by a design team. Goals are used to structure the design space, direct efforts, and limit possibilities, but they are non-mandatory and must frequently be sacrificed in order to meet the less negotiable requirements passed down by a client organization. This can be effectively illustrated in looking at the design of a component by a supplying organization. The previously discussed timing constraints imposed on suppliers by Dell are meant to ensure that the necessary components are available and present in order to facilitate the assembly of a computer. Suppliers can impose a number of constraints in an effort to improve their efficiency, reliability, or profit margins, but it is likely that many of these goals may go unmet in the face of Dell's needs for components to arrive 'just in time' for assembly. While all of these constraints are of the imposed, rather than inherent variety, there is clear variation in the ability of designers to control or change these constraints.

Looking broadly at design constraints across a number of disciplines, authors like Gedenryd and Lawson have noted a pattern in the negotiability of constraints. The degree to which constraints are adaptable by designers is directly tied the source of a constraint: "…the

further away from the designer the source of a constraint is located, the less control of it does the designer have, and the less flexible is the constraint…" [55]. As an example, constraints imposed by regulations are "…beyond the influence of designers…" while client–imposed constraints are less negotiable than the constraints imposed by designers themselves. While this hierarchy of constraints is certainly not immutable, this general pattern seems to fit with the most common view of the design process, with less negotiable requirements being passed down from governing bodies and clients, and goals and objectives being applied by design teams. Gedenryd points out that in the negotiation of conflicting or competing constraints, the more negotiable and flexible constraints (designer imposed, and occasionally client imposed) are most frequently the ones that are compromised—not because they are less important, but because they can be most easily controlled by designers.

Lawson calls attention to the special role of the most flexible designer–imposed constraints, saying that "…one of the most important skills designers must acquire is the ability to critically evaluate their own self-imposed constraints" [111]. This is indeed true, as the negotiability of the constraints imposed by designers extends not only to the modification and prioritization of each constraint, but also to whether a constraint is addressed at all. In this way, a designer's *constraint focus* (the set of constraints which designers choose to address; and that set's prioritization) is not something that is determined at the outset of the process, but rather something that emerges over the entire course of a design project. The constraint focus of a designer or a design team shifts, grows, and changes in large and unexpected ways throughout the process—only becoming fully established at the moment the design is finalized. It evolves alongside the designer's understanding of the problem and the design solution itself.

In his classic text *The Reflective Practitioner*, Donald Schon introduces his view of the design process, describing design as "knowing-in-action" and saying design knowledge is "…revealed in and by actual designing." Schon positions the act of design as a *reflexive conversation* with a design situation, stating: "Designers… are in transaction with a design situation; they respond to the demands and possibilities of a design situation, which, in turn, they help to create" [169]. At its most basic level, what Schon proposes is that every design move (an idea, sketch, model, or prototype), has both a productive value and an inquiring learning value [55]. Every sketch, for instance, serves to produce a result: to capture or communicate an idea. It also allows the designer to see the unanticipated consequences of their idea and the limitations of

their current problem formulation, in ways not possible before the idea is actually given form. This naturally allows the designer to adapt their solution attempts (new ideas) and their understanding of the problem they are attempting to solve. It is in this way that design actions advance the understanding of the design situation. What this leads to is a sort of moving—seeing—moving paradigm, in which every move made by a designer yields information which shapes the designer's understanding of the design problem which, in turn, shapes all future design moves, and so on. In this way, Schon describes a reflexive conversation in which the formulation of the design problem and the solution co-evolve over the course of the design process, with a designer's actions serving as the source of exploration and learning [64].

In many ways, a similar reflexive process is also indicative of how constraints are leveraged: they are imposed by designers, and as a result of their imposition they shape a designer's understanding of the problem and the solution. This, in turn, shapes the designer's understanding of the relevant constraints, and alters the way in which those constraints are implemented and addressed in the future. Constraints are frequently inserted, retracted, and modified as a way for the designer to impose structure which leads to a new understanding or framing of the problem. In this way, the set of constraints that a designer is focused on (and its prioritization) informs all design activity, and is in constant co-evolution with the problem setting and the design solution. Further, the imposition of constraints affects both the designer's framing of the problem and the subsequent design possibilities.

This can be illustrated by looking at the problem of material selection for the body of a digital camera. The material choice itself (say, a high–end engineering thermoplastic versus aluminum or magnesium) is directly affected by physical constraints such as the weight of the camera and its rigidity, as well as the ability of the body to keep the camera's sensor shielded from all light. But the decision about which material to use for the camera body also interacts with market constraints: the cost of the material itself, the state of the firm's current manufacturing processes (can they be adapted to produce the body from a new material?), as well as the material's ability to compete with competitor's products (can a thermoplastic body compete against higher quality metal bodies in the hobbyist market?). These questions must all be addressed. At the same time the physical constraints established by this decision affect future use constraints such as the weight and feel of the camera—hobbyist photographers tend to want a substantial camera that has enough weight to eliminate camera shake, but not so heavy that it

becomes a burden to carry. Technological constraints are also affected, particularly with respect to the fabrication of the body.

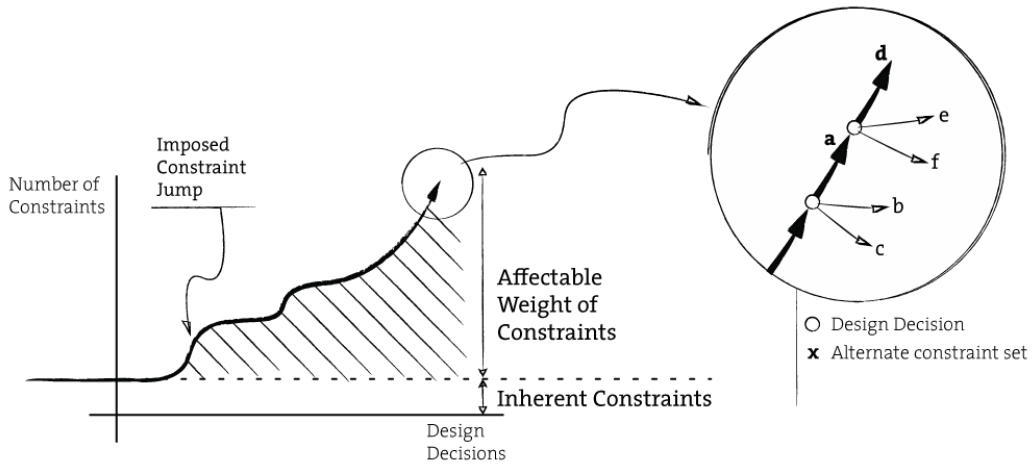


Figure 3.25: The weight of constraints and how design decisions affect subsequent constraints and directions.

Through this example, one can see how every design decision helps to further define the artifact itself and establishes constraints that interact across the constraint classes. *Every design decision creates a more highly constrained environment in which all future design decisions are made.* While it is possible to operate relatively free from constraints early in the design process, constraints become numerous and more difficult to navigate very quickly as the effects of even small design decisions begin to pile up. As those design decisions and their created constraints begin to interact with one another across all five of the constraint classes, the act of balancing these constraints becomes even more difficult. One could even say that any singular design decision is an attempt to manage the existing constraints, but at the same time imposes new constraints whose consequences designers are forced to consider and balance throughout the remainder of the design process.

While every design decision creates new constraints, the constraints that are created can, and do, vary based upon the particular decision that is made. The result is that not only does the cumulative *weight of constraints* [113] increase throughout the design process, but that different design decisions greatly affect the makeup of the set of constraints that comprise this "weight." Accordingly, the set of constraints that designers must address and balance is not one that is set in stone at the outset of the process: each successive design decision has the potential to vary the

constraint set, thereby affecting possible future design directions. Revisiting the case of the digital SLR, the choice of material for the camera body might initially be constrained by price, feasibility of manufacture, and material properties, but that still leaves the designers with many possible choices. Steel, thermoplastic, magnesium, aluminum, a carbon composite, or a number of other materials are all viable candidates at the project's outset. However, once a given material is selected, a number of new constraints are imposed that will affect the remainder of the design process. The designer's potential choices about manufacturing methods, camera architecture, fit, finish and tolerances, as well as the weight and feel of the camera are all constrained differently depending on the initial choice of material. Every subsequent design decision increases the weight of constraints, but it is crucial to recognize that this is not a steady climb that proceeds without consideration for the decisions made. Each decision, each new constraint, uniquely eliminates future possibilities and creates others, and as such designers must be cognizant of this interplay. Additionally designers are not locked into their previous decisions, and are free to explore alternative constraints and design formulations.

This is ultimately a more authentic picture of how design occurs, with the constraint set serving as a way to recognize and provide structure to the set of factors that underlies a designer's understanding of the problem, informs their design process, and guides their valuation of the current state of a design solution. While this structure has, to this point, existed implicitly within the design process—design has proceeded just fine prior to the introduction of this constraint framework—there are certainly benefits to explicitly recognizing these factors. The majority of these benefits are related to the designer's ability to understand and manage the complexity inherent within artifact systems. If we are to view a design problem in its full fidelity, we must view it as encompassing the artifact, its context, and all of its users. In doing so, however, design becomes messy and a far more complicated task. But this is necessary if we wish to produce designs that will be better aligned with the *actual* challenges, opportunities, and needs that are present within this larger unit of design. Accordingly, the value of the constraint framework lies in its ability to assist designers in developing and exploring the true structure of design problems in complex artifact systems. The constraint framework is a systematic and tractable way of understanding and exploring a design space, and managing the effects of complexity on the factors relevant to the design and implementation of physical artifacts.

In conclusion, constraints are neither a hindrance nor an advantage; not solely fixed, or completely flexible. Some constraints exist within the design problem, while others are imposed by the adaptive agents that exist within complex artifact systems. In this alternative formulation, constraints are a powerful instrument, through which designers can affect every aspect of the design process—shaping their own understanding while providing direction for exploration and ideation. Constraints imposed by designers must be viewed not just as goals, but also as a way to explore a design space, test the value of possible solutions, open new possibilities, and provide direction. While some constraints are certainly inherent to the design problem and inflexible in nature, many others are imposed by individuals to serve a particular purpose. These constraints can be inserted, flexed, lessened, or removed entirely in pursuit of a constraint focus and solution that meets the demands of a particular context. Constraints are certainly not static, and they develop throughout the design process in concert with their function. They evolve in step with the designer's understanding of the problem, and the solution itself. Constraints underlie what it is to design.

Chapter 4: Into the Constraint Space

4.1 A Holistic View of Constraints

Dieter Rams is broadly recognized as one the most influential and well-regarded industrial designers of the twentieth century. Many of his works—from calculators and radios to appliances and furniture—are now viewed as design icons, and displayed in museums around the world. While he has notably worked with Vitsœ and Zapf, his name is most synonymous with Braun, the German electrical appliance company, for which he served as lead designer for over forty years [170]. While at Braun, Rams and his designers initiated what the San Francisco Museum of Modern Art called, "…a new wave of holistic attention to domestic products, forever changing the relationship between design and the consumer" [171].

Over the course of his career, Rams was responsible for designing, or overseeing, more than five hundred products. Each of these designs gives a glimpse into Rams's personal design philosophy, which is characterized by the pursuit of simplicity. Speaking for Braun, Rams commented, "We are economical with form and colour, prioritize simple forms, avoid unnecessary complexity, do without ornament. Instead order and clarification. We measure every detail against the question of whether it serves function and facilitates handling" [171]. This philosophy has influenced a whole generation of designers, but has recently received significant attention because of Rams' influence on Jonathan Ives, lead designer at Apple. Ives's designs for Apple reflect Rams's passion for 'simplicity' and 'honest design,' and a number of now iconic Apple products—from the iPod to the iMac—are clearly inspired by decades old Braun designs [172].

Figure 4.1: Comparing the Braun T3 pocket radio and iPod, and the Braun T1000 radio and PowerMac G5 [172] .

Concerned with the current state of design, and citing "…an impenetrable confusion of forms, colours and noises," Rams posed the question: what is good design? As 'good design' is quite a nebulous idea, Rams expressed ten principles that he deemed critical. Occasionally referred to as Dieter Rams' ten commandments of good design, these statements are practical maxims for almost every design context. While obviously not a complete list, the ten principles include relevant truths [173]:

> **Good design is innovative:** The possibilities for innovation are not, by any means, exhausted. Technological development is always offering new opportunities for innovative design. But innovative design always develops in tandem with innovative technology, and can never be an end in itself.
>
> **Good design makes a product useful:** A product is bought to be used. It has to satisfy certain criteria, not only functional, but also psychological and aesthetic. Good design emphasizes the usefulness of a product whilst disregarding anything that could possibly detract from it.
>
> **Good design is long-lasting:** It avoids being fashionable and therefore never appears antiquated. Unlike fashionable design, it lasts many years – even in today's throwaway society.
>
> **Good design is thorough down to the last detail:** Nothing must be arbitrary or left to chance. Care and accuracy in the design process show respect towards the user.

Good design makes a product useful positions the artifact as one component of the larger unit of design, and evidences the need to balance a number of constraints in order to meet the goals and needs of a user within an ongoing field of activity. *Good design is innovative* highlights the designer's pursuit of innovation, but stresses that this can only occur in concert with other

factors. While Rams stresses technological constraints, innovation can occur in concert with other types of constraints as well. *Good design is long-lasting* is a topic that will receive a considerable amount of attention later in this chapter. Shifting our attention to the final listed principle, we see the need for designs to be consistent and thoroughly considered in every aspect of their design. In the film *Objectified*, Rams restates this principle, which is translated from his native German: "Good design is consistent in every detail" [174]. It neglects no aspect of the whole, is consistent across all of its factors, and leaves no stone unturned. This principle, like many of the others, contains a great deal of truth, and can be extended to the discussion of constraints. It is in no way a stretch, to expand 'good design is consistent in every detail' to say that *good design is consistent across all of its constraints*. Any good, or successful, design must, to some degree, satisfactorily address and balance constraints across all five of the constraint categories.

Constraints and the constraint framework are only valuable when we view them as a complete and interacting set of factors. Just as the artifact can only be viewed in concert with the rest of the larger unit of design, so too can constraints only be viewed in light of the other constraints which make up the design space. Successfully addressing any single constraint, or constraint category, in no way guarantees a good design. As Dieter Rams stated, "…it has to satisfy certain criteria, not only functional, but also psychological and aesthetic." It must also satisfy criteria that arise from the likes of manufacturing, distribution, and the market as well. Design is not just about the product. It is about addressing issues that arise at the intersection of the artifact, user, and context, and are dependent upon the design, manufacture, distribution, and sale of that artifact. The success of any artifact is dependent upon a complex set of constraints, inextricably intertwined to the point where organizations and teams of designers have to get so many things right that it is a wonder anything ever gets designed at all.

A solution which adequately addresses every technological and physical constraint but fails to account for usage constraints is unlikely to succeed. So too is a design solution that identifies and builds around a set of constraints derived from only one part of an artifact's life-cycle. Alternatively, a design *can* fail as the result of a failure to address any of the constraint categories. To oversimplify, an almost perfectly designed product—with flawless usability and beautiful aesthetics—is still quite unlikely to succeed if it costs a fortune to purchase or produce. Conversely, there are countless examples of inexpensive products that have not succeeded as the

result of corners cut with respect to usage, technological, or physical constraints. Both innovation and failure can be initiated by any of the constraint categories.

This does not mean that all constraints, or even all constraint categories, are of equal importance for every design problem. There are certainly times where one constraint category will, and must, dominate. In fact, this is likely the norm for any real-world design problem defined by hundreds of constraints. Within such a space, even assuming that one can identify every possible constraint is misleading, and designers are forced to define a constraint focus: identifying and directing efforts towards the constraints deemed most worthy of their limited resources. Similarly, it is impossible for designers to identify a solution that addresses *every* constraint with the same level of quality. When constraints conflict, something must be sacrificed, and some manner of prioritization—whether explicit, or not—is necessary in order to decide which solutions best meets the larger design goals.

In the creation of an airplane, the design of the cockpit and control interfaces is very important, but clearly less so than its ability to fly—as control is only relevant if designers can keep the plane off of the ground. Additionally, while passenger comfort is important, it is clearly less important than both keeping the aircraft in flight and the pilot's ability to control the plane. Hence, constraints related to flight—weight, aerodynamics, etc.—will generally take priority over constraints related to control—cognitive and physical ergonomics, primarily—which supersede constraints related to passenger comfort. Thankfully, the constraints related to controllability and flight can be adequately addressed simultaneously. Passenger comfort, on the other hand, frequently bumps into constraints related to flight, as one of the cardinal rules of designing passenger aircraft is avoiding added weight. Adding more comfortable seats is simply not an option if it increases the plane's weight in a way that hinders flight, efficiency, or profitability.

This is not say that airplane designers should not strive to develop planes that are safe and easy to fly, or solutions that are comfortable for the passengers and crew. Good design requires focus and prioritization over the set of all possible constraints, and consistency across each of the five constraint categories. Even in situations like the design of an airplane, where there is a clear prioritization of one or two areas, the other categories of constraints cannot be disregarded. The plane's ability to sustain lift and fly safely clearly dominates an airplane's design, but efficiency, for example, is an inescapable market constraint. Similarly passenger comfort can be an important factor in the success or failure of an entire airline. Without consideration for the

aforementioned controllability, planes will crash in spite of their being physically capable of flight. These design details, when viewed individually, may seem straightforward in their solution (constraints on passenger comfort are easy to address when viewed in isolation), but when viewed in light of the complete set of constraints, balancing these details makes up a large part of what it is to design.

At this point, it is useful to raise a few questions. What does design look like without constraints? And how does a holistic view of constraints shape the understanding of design? As previously discussed, constraints give structure to design problems, limit possibilities, and provide focus to designs. Looking at biological evolution as a corollary, "if there were no constraints on what is possible, the best phenotype would live forever, would be impregnable to predators, would lay eggs at an infinite rate, and so on" [175]. Without constraints in design, every solution would be ideal. It would do everything, and do everything well. The ideal airplane would comfortably accommodate as many passengers as needed, consume no fuel, and never crash as the result of technical or operator errors. In reality, this is not possible as the result of constraints.

Inherent constraints, such as the law of conservation of energy, are obvious reasons this is not possible. Beyond those inherent in the design space, the actual act of designing an airplane is carried out through the imposition of constraints. Clients and regulators impose constraints and specifications of minimum performance, while engineers and designers explore constraints and make decisions with regard to wing shape, material selection, manufacturing processes, and so on [45]. Further, decisions about all of these constraints must be made under the influence of daunting market constraints. For example, a plane cannot be built without consideration of manufacturing cost, operating cost, and efficiency. As Dawkins states, "…the aeroplane wing must not break until it receives a stress three times what would be expected in worst-case turbulent conditions; now go ahead and build it as cheaply as you can…. In effect, the engineer's optimization instructions amount to a monetary evaluation of human safety, speed, convenience, pollution of the atmosphere, etc. The price put on each of these is a matter of judgment, and is often a matter of controversy" [176].

Here Dawkins recognizes two very important things: cost and judgment. While the task of designers cannot often be classified as pure optimization, the selection and prioritization of constraints in pursuit of increasingly good solutions is a huge part of the design process. There

are a large number of possible constraints simultaneously vying for designers' attention, and there is only so much time and so many resources that one can devote to exploring and addressing those constraints. In this sense, design is very much about the *selective* imposition of constraints. Returning to biology, Dawkins concludes that, "…every evolutionary adaptation must cost something, costs being measured in lost opportunities to do other things" This is reminiscent of the previously discussed optimality-brittleness trade-off. In the face of limited resources every design decision and every constraint addressed represents a cost. Making an airplane lighter has implications on its size and the number of passengers it can carry, or else the materials of which it is made. Changing the material in order to avoid reducing capacity will likely increase the monetary cost of the airplane, not to mention any effects on the manufacturing processes and failure modes associated with the new material.

It is simply not possible to address a constraint in isolation, as every decision regarding which constraints to focus on, how to prioritize those constraints, and how to address those constraints is made at some cost. Focusing on technological constraints related to flight limits the focus that can be devoted to issues of usage (by pilots, staff, and passengers), or at the very least necessitates additional costs associated with the engineers responsible for addressing these additional constraints. Prioritizing constraints related to safety limits designers' ability to address issues of performance, while choosing a particular wing shape precludes all other wing shapes. Every design decision that is made limits and constrains other possibilities. Every design decision has some cost, whether that cost is paid in resources, design opportunities, or capabilities in the context of use. Any view of design which does not recognize these costs and trade-offs is ultimately doomed.

Every successful design must *satisfactorily* address enough constraints to satisfy an artifact's stakeholders. A 'good design' is not necessarily the single best solution, it does not successfully address every constraint, and it is certainly not optimal. It manages to find a balance and is 'good enough' with respect to the full constraint set. Every artifact's story of design, fabrication, adoption, and use is marked by all relevant categories of constraints as they interact within a complex artifact system. An understanding of 'good design' is an understanding of the complete set of constraints. It is inherently holistic, balanced with respect to costs and trade-offs, across all levels of the artifact hierarchy, for all stakeholders, across a design's entire life-cycle.

4.2 Constraints and Fitness

To this point, I have stressed the value of design solutions that 'perform adequately', are 'successful', or are what Dieter Rams calls 'good design.' None of these phrases are particularly descriptive, however. Integral to each is an underlying sense of design quality. Nonetheless, the 'quality of design' still does not do much to reduce the ambiguity. While we can never fully escape the subjectivity or qualitative nature of design, it is possible to discuss 'quality of design' more rigorously, in a way that is better suited to our current exploration.

If one thinks of the word *designed*, they are likely to think of objects, artifacts, and other constructs created for a specific purpose, which attempt to address an opportunity or problem that exists in a field of activity [12]. A knife is designed to cut, a screw to secure, and a screwdriver to turn a screw. If one considers what it is to produce 'good design,' or considers designs which 'perform adequately,' they are likely to think of artifacts not simply designed for a purpose, but rather those that are *fit* for that purpose, task, or context. A screwdriver, if designed to cut bread, would in no way represent a 'successful' design solution. A screwdriver is a much more 'adequate solution' to the problem of applying torque in order to secure a fastener. Between these extremes, there are also a number of other tasks that a screwdriver can do—opening a can of paint, for example—but for which it is less than ideally suited. A screwdriver can only be seen as fit to its purpose with respect to a particular context, defined by some individual's desire to drive a screw for a particular purpose—to hang a picture, for instance. This fit is also dependent on other contextual elements, such as the screw to which it mates. Without a matching screw, the screwdriver is certainly not a good solution, as it would be decidedly impractical to drive a nail with a screwdriver—despite the fact the user's desire to hang a picture remains unchanged.

Within this spectrum of tasks, it is possible to explore the concept of *fitness* in order to better investigate and communicate the 'quality' of a design solution. Fitness is a well-established concept that has been successfully deployed in the study of everything from anthropology and linguistics to economics [12] and design [4], [38], [177], but its origins lie in evolutionary biology. The original inception of the idea can be traced back to English sociologist Herbert Spencer, who coined the phrase *survival of the fittest* in 1864 [178] in an attempt to characterize the process of natural selection. Originally, the concept was used to describe an "…organism's vigor, or the degree to which organisms 'fit' into their environments…," which was distinguished by its ability

to find food, avoid predators, and survive within a given ecosystem [179]. Eventually, biologists extended the concept of fitness beyond the ability to survive and mature to include the organism's ability to beget successful offspring—both in number and *their* ability to survive [180]. Essentially, 'fit' organisms are more likely to survive and reproduce; 'unfit' organisms are unable to pass their genes on to future generations, as they are more likely to be captured by predators, or succumb to the harshness of a particular environment.

At its core, fitness "…describes the relationship of an organism to its environment…" [179]. Accordingly, it is possible to extend the concept to other domains. "The fitness of a system is a measure of whatever combination of attributes gives the most 'benefit' in the current circumstance. This could be survival to reproductive age (biology), financial profit (business) or popularity (music groups)" [16]. With respect to the design of physical products, fitness can easily be used as a descriptor of the degree to which an artifact is fit to its purposes and context. A 'fit design' is well suited to its current application and context of use. A design that is 'unfit' to its current context is less likely to serve its purpose within that context. "The larger fitness is, the better or more suitable is the product to the users in context… [it] is related to the match between the design and the user goals and activities" [78].

If we are to view design as acting on more than just the artifact, we must understand a design's 'fitness' as a fundamental *relationship* between the product and its environment, which includes stakeholders and contexts of use. The process of design, then, can be understood as a search for fitness between an artifact and its context. In *Notes on the Synthesis of Form*, Alexander characterizes the activity of design [4]:

> Every design problem begins with an effort to achieve fitness between two entities: the form in question and its context. The form is the solution to problem; the context defines the problem. In other words, when we speak of design, the real object of discussion is not the form alone, but the ensemble comprising the form and its context. Good fit is a desired property of this ensemble which relates to some particular division of the ensemble into form and context.

He continues:

> There is a wide variety of ensembles which we can talk about like this. The biological ensemble made up of a natural organism and its physical environment is the most familiar: in this case we are used to describing the fit between the two as well adaptedness. But the same kind of objective aptness is to be found in many other situations…. An object like a kettle has to fit the context of its use, and the

> technical context of its production cycle…. The rightness of the form depends, in each one of these cases, on the degree to which it fits the rest of the ensemble.

The fitness of any construct, and every designed artifact, relates to its 'well adaptedness' to the situation for which it has been created. That situation, however, is multi-faceted and amorphous. It is the product of any number of relevant factors that range from obvious to obscure, and it originates from every part of the larger complex artifact system. One might even say that the context against which a design's fitness is judged is the *product of an innumerable number of constraints*. These constraints define not only the boundaries of what is possible, but also what is 'fit' for that particular intersection of artifact, stakeholders, and context.

Although a design's fitness is measured in its relation to a set of constraints, it is still very much reliant upon designers addressing individual constraints. These constraints can each be addressed in a variety of ways, and there are an innumerable number of ways in which these individual constraints can be combined to create a complete design solution. The fitness of a marine creature, for instance, depends in part on its ability to address the constraint of evading predators, and evolution has provided a multitude of ways in which this constraint might be satisfactorily addressed. Many marine organisms, for example, have evolved the ability to swim and quickly change directions in order to evade predators. Some have learned to school together in order to maximize their individual chance for survival. Still others use the surrounding environment to their advantage, hiding within the crevices of the reef, or camouflaging themselves with the environment. However, other organisms like muscles, mollusks, clams, and urchins have sacrificed mobility and camouflage in favor of the protection of hard (and sometimes dangerous) shells.

Each of these alternatives represents a potential way of avoiding predators, as there are organisms that rely on each of these strategies. But these alternatives do not, in and of themselves, represent fit organisms, and there are certainly configurations and alternatives that are more preferable to others. This is because a design's fitness is not just determined with respect to one specific constraint or dimension; it is dependent upon multiple constraints simultaneously—it is holistic in nature. Just as an organism that lives in the ocean certainly benefits from the ability to breathe underwater, if that same organism is unable to evade predators, or find a mate, it is unlikely to be seen as fit to its environment. In design the same is

true: a knife blade will benefit from a sharp edge that facilitates its ability to cut through some material, but if that same blade cannot hold an edge, or does not have a proper handle with which it can be wielded, it is unlikely to be fit to its purposes. Addressing individual constraints is important, but each is only one small building block on the way to achieving fitness with respect to a full ensemble of constraints.

In light of the constraint framework, an artifact's fitness can be more readily described in relation to the set of constraints which condition its creation and use. In this way, the constraint framework is suited to categorizing the factors which characterize the fitness of a designed artifact. The design of a fit knife, for example, must not only be fit to the set of usage constraints (chopping without injuring), but also to the constraints that arise within the other four categories. It must strike a compromise between hardness and sharpness, and be balanced to allow for dexterous use. It must be made of a material that resists corrosion, allows for cleaning, and facilitates its fabrication at appropriate costs and volumes. The aesthetics of the knife must fit within the specific cultural context, and imply its use and operation. In addition, it must not infringe on patents or the proprietary positions of other knife manufacturers, else increasing costs or blocking sale. While this is certainly not a complete list of every constraint that must be addressed in the design of a 'fit' knife, these represent a number of the factors that make up its constraint context. Notably, it is this fitness to a particular constraint context that separates successful design solutions from unsuccessful design solutions. 'Good design' is to strive for fitness across the entire ensemble of constraints.

Kim Clark recognizes the holistic nature of fitness and illustrates the role of diverse constraints with an example from automobile design in turn of the century America [54]:

> In this case the general context was the economic and social environment of late 19th century America, but its more specific dimensions involved the state of roads, the patterns of commerce, geography, and the habits and preferences of customers with respect to transportation. The form – the emerging automobile – can be defined in terms of its basic functional parameters: motive power, steering, stopping, regulation of speed, load capacity, and so forth. Each parameter pertains to a functional domain, but within any particular domain, there exists a set of alternative concepts among which the designer may choose.

This holistic fitness is a direct result of the relationships that exist amongst the individual constraints that make up a design problem. Concerning ourselves with only the ability of a marine organism to avoid predators can be seen as analogous to a design process with a single constraint (or a set of completely independent constraints, as each can be addressed in isolation one after the next). In the design of a physical product, this lone constraint might be performance, speed, cost, weight, or any number of others. Regardless of the chosen constraint, in each instance there are a number of possible ways to achieve the same end. Suppose that in the design of the Mars rover *Curiosity*, the only relevant constraint was to minimize the weight of the rover's frame. Engineers could remove a few screws, change the material of which it is made, reduce the thickness of a component, reduce the overall size of the frame, or integrate the functionality of two parts into one—all to the same affect. If the only constraint is weight, none of these solutions is necessarily better than any another, so long as the final solution weighs the same. But in reality, design problems with only one constraint simply do not exist, because constraints that arise throughout the entire artifact system influence one another—they are mutually related.

Designing the Mars rover's frame to be as light as possible is, on its own, not a daunting task. But the introduction of even one additional constraint (that the rover must survive impact on the surface of Mars) however, makes arriving at a viable solution considerably more challenging. These two related constraints must now be simultaneously addressed, and decisions made with regard to the second constraint are directly tied to how designers choose to address the first. If they choose to limit weight by reducing the amount of material, the rover's frame may lack the rigidity to survive impact on the planet's surface. Thus, they must now design a way to slow its descent, or soften its impact. Similarly, marine organisms must balance the constraints imposed by the need to reproduce against its chosen method of protection. Swimming is a plausible way to search for a mate, but if the organism protects itself with a stationary fortress—as in the case of a sea urchin—a new means of reproducing must be selected.

Regardless of context, any fit design must confront multiple constraints *simultaneously*. There is a give and take with respect to how individual constraints are addressed within the larger design, and there are often critical constraints that must be addressed with some minimum level of satisfaction. Further, constraints frequently present challenges that are not easily addressed without causing difficulty for other constraints. These decisions about how to address

individual constraints within the context of a larger design are the costs mentioned by Dawkins, and the trade-offs covered in *Chapter 2*. In design there are countless examples of constraints that are seemingly contradictory: weight and durability, size and power, performance and reliability, but there are many others that are considerably less apparent. Constraints, in the design process, exemplify trade-offs. Addressing one constraint can lead to problems with another; movement in one direction requires sacrifices in another. This is an example of the previously discussed optimality-brittleness trade-off: designs becoming more optimal to some constraint while becoming increasingly brittle with respect to another. In many ways, design fitness is all about managing trade-offs [91].

The design process, as a search for fitness, is all about balancing decisions—about things like structure, features, capabilities, and how to accomplish those things—with respect to the other constraints that exist within the design problem. This search for balance, however, always takes place in the face of limited resources, as each constraint competes for the focus, time, efforts, and resources of designers. Accordingly, the priority given to each constraint often plays a large role in the form of a solution, and the relative importance given to each constraint is very much up for debate within the design process. In the design of the Mars rover, one engineer may feel that weight is more important, and another may feel strongly about its durability. Still, while it is possible to prioritize certain constraints, and ignore others, any solution to a real-world design problem must *satisfactorily* balance competing constraints.

Real world design problems embody innumerable constraints, and each constraint makes up the environment by which every other constraint will be judged [16]. Thus the way in which designers choose to address one constraint has an impact on what is appropriate in addressing many others. Design is not about picking a set of features that are entirely independent from one another—addressing constraint A, before turning attention to constraint B, etc. It is about finding a way—through creativity, intuition, analogy, and persistence—to produce an ensemble that satisfactorily addresses all of the constraints, even the ones that seem incompatible. It is about striving for fitness to a purpose and context in the face of uncompromising constraints.

Each solution must not get every constraint "right," nor must it address every constraint to the same degree. Instead, any design solution must strike a balance within this multidimensional constraint space. Even given the same high-level design specification—to design a knife or an inter-planetary rover, for instance—there are an almost infinite number of

'fit solutions' to each problem. There are countless knives currently fulfilling their purpose in the lives of individuals across the world. Similarly, while NASA only developed one version of *Curiosity*, there are almost certainly any number of alternate configurations that would have also worked, should that have been the solution at which NASA engineers arrived. The solution they did arrive at, however, worked in conjunction with the totality of constraints.

If there are, in fact, multiple ways to achieve fitness, this raises questions about what fitness actually communicates, why it is valuable, and how it might be employed in the context of design activity. In biology, fitness tends to be a difficult concept as the result of the multiple ways in which it has been defined and used. It can signify everything from the capacity to survive and reproduce to a mathematical representation employed by population geneticists [176]. In design, however, fitness cannot be employed as a measure of survival or reproductive success in any classical sense, as artifacts are not organisms reliant on survival and reproduction. So why even bother with the concept of fitness?

In design, just as in biology, fitness is not purely a binary measure—ideas and products are not exclusively fit, or unfit. Instead, fitness is most valuable when used as a tool for comparison. A design cannot typically be referred to as wholly fit or unfit, rather it is more convenient to describe a product as 'more fit' than another. Although it is possible to talk about design in absolute terms, doing so holds little utility. A screwdriver is more fit for the task of turning a screw than is a butter knife. The Apple iPod was more fit to the market than was the Microsoft Zune, as evidenced by its 78% market share [181]. Any single idea, prospective solution, or concept is difficult to evaluate on its own. What does it do well, will it perform adequately, are the ideas original, etc.? These are all hard questions to answer in a vacuum, but in the presence of other ideas or solutions, it is much easier to judge fitness. The design process is about striving for fitness in an attempt to develop artifacts and ideas that are more fit to a particular context. It holds more value as a direction of progress than it does as an unchanging measurement, and it offers utility to designers in light of the challenge of becoming more fit. Within the design process, each idea, each concept, and each design iteration strives to be more fit than the last. Once released into the market, an artifact strives for comparative fitness within a constraint environment established by competitors, every artifact that has preceded it, and all artifacts that will come after.

Most designers do not think of the design as a process as an attempt to maximize fitness with respect to a set of constraints. While at some level, this is what is happening, it is potentially problematic to think of fitness as something that should be *consciously* strived for. Fitness, for our purposes, is an illustrative metaphor intended to facilitate understanding and discussion. The design process, at least in most instances, is not about optimization, and it does not specifically attempt to maximize anything. Instead, the design process attempts to continually improve performance with respect to the full complement of constraints. While these two statements may seem similar, there is a meaningful distinction: designer's and design processes may behave *as if* they are attempting to maximize a design's fitness, but in reality they are doing nothing of the sort [176].

Going back to biology, an organism's fitness is judged with respect to its environment; but that context is not dependent solely upon the structure of its physical environment, climatic conditions, or even available food sources. Instead, that environment is constituted of the physical environment and conditions, in concert with all of the other organisms that inhabit that environment. Every genotype is tasked with survival and reproduction in relation to all of its competitors. This includes classical competitors—predators and prey, with whom the organism relies on for sustenance and avoids for survival—as well as organisms less frequently viewed as competitors—other organisms within the same species, and other species with whom the organism shares a food source. A giraffe's fitness is not judged solely on its ability to reach the trees for food, or its ability to withstand drought. Its fitness is judged against an environment that includes every other organism with which they share the savannas. Lions, and Nile crocodiles are an adult giraffe's primary predators, but in its lifetime, a giraffe also must contend with predation from leopards, hyenas, and a number of other wild dogs [182]. Additionally, we must also consider other giraffes, and the other organisms with which the giraffe competes with for food and water. Each of these is an integral part of the context against which a giraffe's fitness is ultimately judged—each imposes constraints on the giraffe's phenotype with regards to survival. Looked at from the opposite perspective, the giraffe is also an integral part of the environment and context against which each of these other organisms is judged as well [16].

Looking at physical products, the Microsoft Zune music player was previously used as an example of a device less fit than the iPod. The Zune certainly was never able to challenge the success of Apple's music player, but taken in a vacuum, the Zune worked quite well as a music

player. It met its requirements, was aesthetically pleasing, and did everything that it needed to in order to satisfy the majority of constraints related to usage, manufacturing, etc. One reviewer describes interacting with his touch screen Zune HD, stating [183]:

> Turn on the device and you're presented with a bright, beautiful, text-only home screen. This is boldly original: Whereas the iPhone and iPod Touch's main interface features a collection of illustrated icons, Zune's design guidelines sought to foreground typography. Microsoft licensed a brilliant, minimalist font called Segoe for the Zune, and the device renders its main functions in large, lowercase type. Tap on each menu item—music, videos, etc.—and you dive into the function with a quick, animated zoom. A text-only menu system sounds like it might be boring, but the typography is so pretty, and the software lets you navigate so quickly, that I found it every bit as functional as the iPod Touch's interface.

By most accounts, the Zune was a good product when taken on its own merits. So what did it do wrong? The single largest problem with the Zune—at least according to Robbie Bach, an executive in charge of Microsoft's Zune division—was that it was released into a market that was already heavily dominated by Apple's iPod. In fact, Bach even said that Apple had killed the Zune *before it even launched* [184]. The original iPod was released in 2001, and by the time Microsoft released the Zune five years later the iPod had already sold 100 million units; it was firmly entrenched as a part of the Zune's context. In 2008, two years after its initial release, Microsoft had managed to sell only 2 million units. During the fourth quarter of that year, revenue from the Zune was reported at $85 million. In contrast, Apple's revenues for the iPod during the '08 holiday season were approximately $3.37 billion. By the time Microsoft retired the Zune in 2012, it was seen as a failure of colossal proportion, and Time Magazine called the Zune, "…one of the ten biggest tech failures" of the 2000's [185]. This is despite the fact that *on its own*, the Zune was a viable solution to the challenge of designing a portable digital music player. It was just not fit to survive in a constraint context already heavily influenced by the iPod, iTunes, and the App store.

4.2.1 Fitness Landscapes, Design Spaces, and the Constraint Space

Another way to increase the accessibility of the fitness concept, particularly with respect to the multi-dimensional nature of the constraint set and real-world design spaces, is to extend

the discussion to what biologists call *fitness landscapes*. The fitness landscape is a visual metaphor, acting as a way to facilitate understanding with regard to fitness in large, complex spaces. As fitness is a result of a holistic set of constraints arising from products, users, cultures, and markets, a better way to envision fitness at the scale of real-world design problems is necessary. The fitness landscape is intended to do just that. First introduced by Sewall Wright in 1931 [186], a fitness landscape represents an *N*-dimensional space as if it has only three dimensions for ease of visualization and discussion. This three-dimensional space represents a space, within which biological evolution searches for fitness.

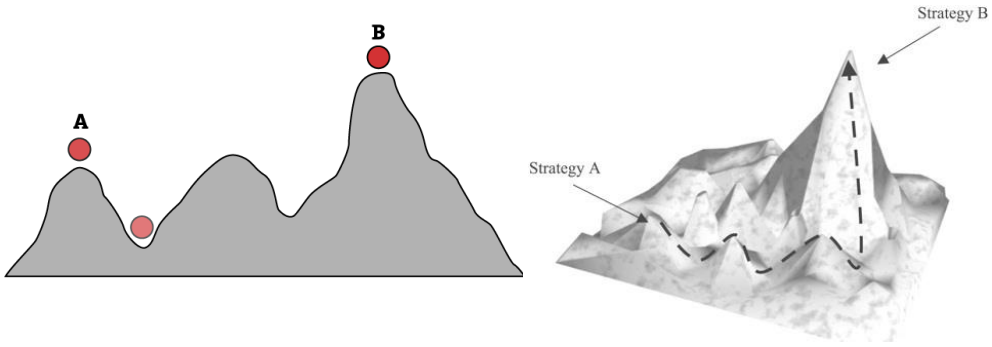


Figure 4.2: Two and three dimensional representations of a fitness landscape [187].

The fitness landscape is designed to represent the relative fitness of organisms in simple three–dimensional form: the better suited an organism is to its environment, the higher it is on the landscape. In *Figure 4.2*, a design positioned at point B is more fit than a design positioned at point A, which is more fit than a design at the valley between A and B. "In these metaphorical places, species climb uphill towards optimal fitness…" through the process of evolution [187]. This space represents every possible 'design' of an organism; every possible genotype. Evolution searches this space for solutions that work—some genotypes are successful others are not, but the space includes every possible combination.

In the context of design, that space is defined by every constraint, and represents every possible way to address those constraints. Designers want to avoid the valleys, and do everything in their power to develop their designs in a way that finds the peaks of the fitness landscape. This fitness space includes every possible combination of ideas, features and design decisions—

every possible artifact [38]. The space is technically finite, in that there are a limited number of ways in which these constraints can be addressed. For the purposes of design, however, it is infinite for all intents and purposes, as it is likely that designers can only explore the smallest fraction of the total fitness landscape—a small proportion of all possible solutions.

In his book, *Darwin's Dangerous Idea* [188] Daniel Dennett provides a particularly clear illustration of a fitness landscape. Imagine that every possible design solution, every possible way of addressing a set of constraints—or every possible genotype in the biological case—has a metal rod positioned vertically above it. The height of that metal rod represents the fitness of the design solution beneath it—the taller the rod, the more fit the corresponding solution. Around that potential solution are other solutions which are quite similar to it, and each is changed in only the slightest way—such that the fitness of each near solution is approximately the same. Changing a design slightly or changing one letter in an organism's vast genetic code, is unlikely to make a huge difference with regard to its fitness. In other terms, a design which is a bit heavier, a bit lighter, a different color, or a centimeter longer is not likely to be considerably more or less fit than the alternative. These differences do occasionally matter, however, as each point, each rod, is only roughly correlated with the points nearest to it [189].

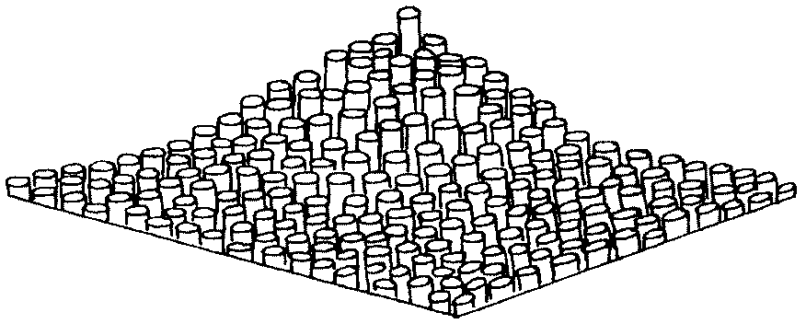


Figure 4.3: Each rod's height represents the fitness of the corresponding design solution [188] .

Repeating this for every possible solution, what results is a vast landscape of rods differing in height according to their fitness—each rod representing one possible solution for addressing all of the constraints on a design problem. As an effect of grouping like ideas near one another, the resulting fitness landscape looks not unlike a real landscape—with

topographical features like mountains, hills, valleys, flatlands, and plateaus—rather than a random arrangement of rods. Within this landscape, we can move from rod to rod—from design to design—and note the change in height of each rod, which corresponds to the change in fitness. "The fitness landscape shows us visually (and to researchers mathematically) where the good designs in a design space are located. We can think of good designs as high fitness peaks, and our problem of finding good designs in the near infinity of design space can be reconceived as finding high peaks in the fitness landscape" [12]. It is necessary, however, to recognize that while the landscape represents a set of all of the possible design solutions, both good and bad, it is not possible to ever fully specify this space—it is, instead, a sort of short hand representation of the complete design space [4].

This raises a number of questions which push the limits of this metaphorical landscape, particularly as it relates to the actual execution of design in real world contexts. An artifact at point B is clearly more fit than an artifact at point A, but what does that actually mean? *How much* more fit is design A, and why does that even matter? For that matter, what is fit enough? Combining the concept of fitness with the constraint framework can allow designers to better leverage each of these concepts. As we have established, the more effectively a design addresses the complete ensemble of constraints embodied in the artifact system, the more fit the solution. Thus it should be possible to further specify and describe the fitness landscape with respect to the specific set of constraints that ultimately determine a design's fitness. The fitness landscape, when combined with the constraints, represents a landscape of all the ways in which those constraints can be addressed—a constraint landscape, or a *constraint space* of sorts.

When viewed in this way, the fitness of any design is fundamentally connected to the constraint space which underlies it. The constraint landscape becomes a metaphorical way to relate the designed artifact to the other two components of the larger unit of design. It fundamentally ties the artifact to its contexts and stakeholders in a more meaningful way than is possible if we are using simply using fitness as a measure of 'good design.' Constraints can help to increase the tractability of the factors which actually determine an artifact's fitness, and they allow for these factors to be better understood. Furthermore, this can better facilitate their recognition, management, and balancing within an actual design process in a way that is not possible with overly vague notions of fitness.

From the beginning, the goal of providing greater focus to design constraints was not to develop a model, a strict design method, or a prescriptive program that could categorize and solve design problems. It was to enrich the understanding of designers and provide them with a new lens through which they can approach, explore, and discuss design problems—potentially leading to more 'fit' solutions. Within this understanding of the constraint space, the goal of designers is to then identify peaks, and do everything that they can in order to position designs at the apex. The design process itself has, in many ways, evolved in order to explore this space, search for opportunities, and identify potentially fit designs.

In order to help designers best leverage these concepts, it is necessary to further explore what the constraint space actually looks like. As mentioned, the fitness landscape is not random because similar design alternatives are grouped near one another. Neither does this mean that the landscape looks like a series of smoothly rolling hills, where the fitness of a majority of designs is approximately equal. If every possible design alternative was not much different from all the others, design would not be such a challenging activity, and most alternatives would suffice. The fitness landscape typically does not look like Mount Fuji either—with all points gradually building into a single giant peak [189]. There generally is not a single global maximum, which is clearly superior to all others. Instead, as Kaufmann suggests, the fitness landscape for all biological and designed things looks more like the Swiss Alps: a cluttered landscape dotted with high peaks and low valleys.

As is the case with ecologically inspired fitness landscapes, there are a number of ways in which a design can make a living and 'survive' in the constraint space, although survival is not guaranteed. Developing fit artifacts requires designers to identify and address the relevant constraints; and doing so successfully can be a highly challenging process. Reaching a peak within the constraint space requires that the constraints and trade-offs be successfully balanced, and that designers successfully navigate a winding and treacherous path. When viewed as a complete landscape, however, fit designs may be found near the top of many different peaks, as there are multiple 'good designs' that simply choose to address the set of constraints in different ways. As fit artifacts can be found at the top of many peaks throughout the constraint space, local maxima (rather than global maxima) are often sufficient for fitness.

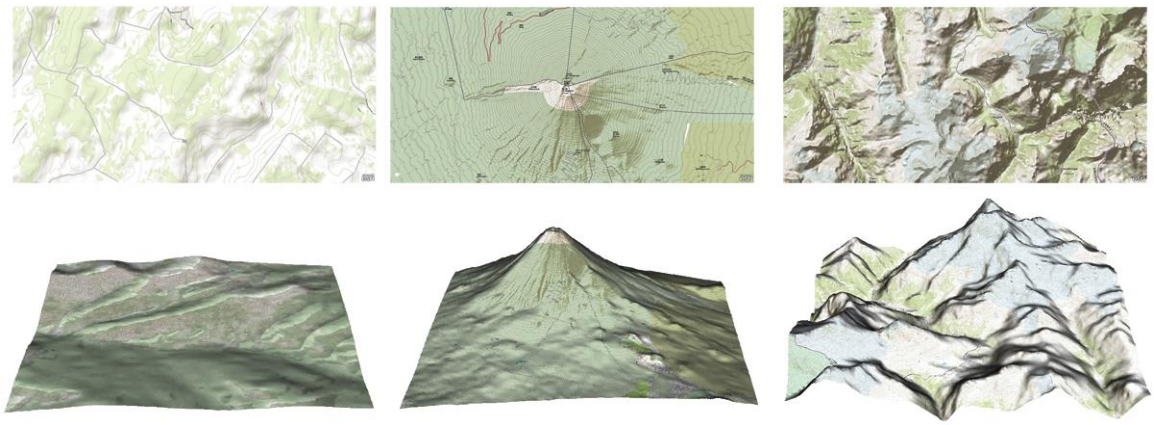


Figure 4.4: The constraint space generally does not look like gently rolling hills or a single giant peak (Mount Fuji). Instead, it is marked by many peaks and valleys (Swiss Alps) [190].

In the search for fitness, designers must not forget that typically they can only exert control over one part of the larger unit of design. Designers have little or no control over an artifact's other stakeholders, just as they have little control over the context in which it is applied. In short, designers do not control the constraint space in which fitness is judged. In most instances, the artifact is the only piece of the system that is under the immediate control of designers. In discussing design as the pursuit of fitness, Alexander states that, "…fitness is a relation of mutual acceptability between these two [form and context]," but that the form is the only part of the world over which designers can exert control—the part "…which we decide to shape while leaving the rest of the world as it is" [4]. This is certainly not to say that the designs and artifacts cannot affect the constraint space. What it does imply is that the design context is typically outside of the designer's *direct* control.

Herbert Simon offers a similar conclusion [38]: "An artifact can be thought of as a meeting point between… an '*inner' environment*, the substance and organization of the artifact itself, and an '*outer' environment*, the surroundings in which it operates…. If the inner environment is appropriate to the outer environment, or vice versa, the artifact will serve its intended purpose"—it will be considered fit. While the inner environment (an artifact's design: what it does, how it does it, its components, its structure, etc.) is the province of engineers and designers, designing fit solutions "…demands an understanding mainly of the outer environment."

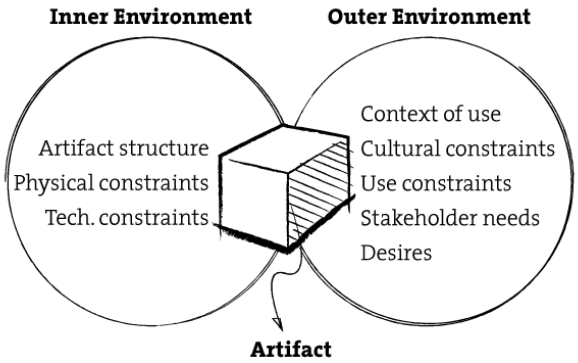


Figure 4.5: The artifact as the interface between an inner and outer environment.

Largely, stakeholders are not concerned with an artifact's internal composition, its structure, or even its 'design.' Stakeholders merely care that the artifact serves its purpose, and provides the desired capabilities within their particular context. Consider typical smart phone users. They care that they can easily place and receive calls, surf the internet, and manage their calendar; they do not typically care about their phone's internal composition, the design of its circuitry, or the particulars of the phone's operating system. Designing products that facilitate stakeholders' desired capabilities, demands that designers have an understanding of the constraints that characterize the outer environment. In doing so, they can appropriately formulate the design of the artifact. Once introduced into the context of use, the artifact can be seen as the *interface* between the embodied design (the part of the system controllable by designers) and the external constraints [38]. The constraint space simultaneously drives the design process, and is the judge of each and every design solution. It is a source of ideas, inspiration, opportunities and limiting factors, but also the determinant of every product's success.

4.3 Structure and Characteristics of the Constraint Space

The goal of the constraint framework and the constraint space analogy is not to explicitly list every constraint that will have some bearing on a design. Nor is the objective to map every interaction that exists between these constraints. Instead, the goal is to help designers to strike a dynamic balance across the constraints, even if they can never be certain of the full set, or all of the ways in which they interact. A 'good design' does not immediately follow a

thorough understanding of the constraint space, but providing designers the tools and a structure with which to creatively explore and understand their unique contexts increases the likelihood of identifying fit design solutions.

In order to design solutions that are fit to a given design problem, it is important that designers first strive for an authentic understanding of the constraint space. Doing so requires a realistic view of the individual constraints, as well as a realistic picture of the way in which those constraints combine together. Oversimplified views of the constraints, or their interactions, can be potentially damaging to the design process, as it hides the complexities that actually produce the system's behavior. This can lead to design directions and proposed solutions that are less than well suited to their design environment [191]. Successful design is about recognizing the relevant constraints, and then balancing them across the full ensemble. Accordingly, it is possible to look to the structures and patterns that exist in the larger class of complex systems—many of which were covered in *Chapter 2*—for a better understanding of how to improve the design process.

4.3.1 The Nearly Decomposable Constraint Space

Complex systems are often described as more than the sum of their parts, and the constraint space is no different, because in both instances it is the relationships and interactions between elements that matter most. Constraints frequently arise as the result of relationships between parts of the artifact system, and constraints are the most significant in their relationships to other constraints [111]. A single constraint, or even a single constraint category, is insufficient to specify the performance of the larger artifact system: the complexity of the constraint space reflects the complexity of the world.

As it is decomposed, the constraint framework serves as a manageable representation of the vast number of constraints at play within a given design opportunity. First, constraints arise from *different locations* within the artifact system. These different points of origin are often quite obvious because the constraints themselves frequently look so different. Constraints whose origin can be traced back to an end-user are generally dissimilar to constraints that result from manufacturing, or from the design organization. For example, the ergonomic constraints that

shape the comfortable use of a kitchen knife can be easily traced to a different source than those related to scaling production costs, or the maintenance of brand identity.

Constraints also arise from *different levels* of the artifact's internal hierarchy. Recalling the hierarchy of physical artifacts, it is likely that the constraints that exist at each level will be different. The constraints that arise at the level of a component typically differ from those originating at the level of the artifact. In the design of a vehicle the constraints that exist on a piston—strength, rigidity, durability, heat tolerance, etc.—are different than the constraints at play for the engine—sufficient torque and horsepower, fit within the engine compartment, etc. Extending this concept to the surrounding system, one continues to see different constraints arise at each hierarchical scale. Viewing a vehicle as a system at a level which includes both the artifact and the activity, the constraints include the ability to haul cargo, transport kids, or out-accelerate another driver. Scaled up to the level of culture or governance, constraints arise with respect to fuel economy and safety regulations. At each level of the system new but important constraints emerge. More generally, a pattern seems to emerge as the five categories of constraints appear to exhibit themselves differently, at different levels of the hierarchy. While in no way a hard and fast rule, there appears to be a trend in that physical and technological constraints tend to dominate at the lower levels of the hierarchy, while market, usage, and socio-cultural constraints are more prevalent at the higher levels.

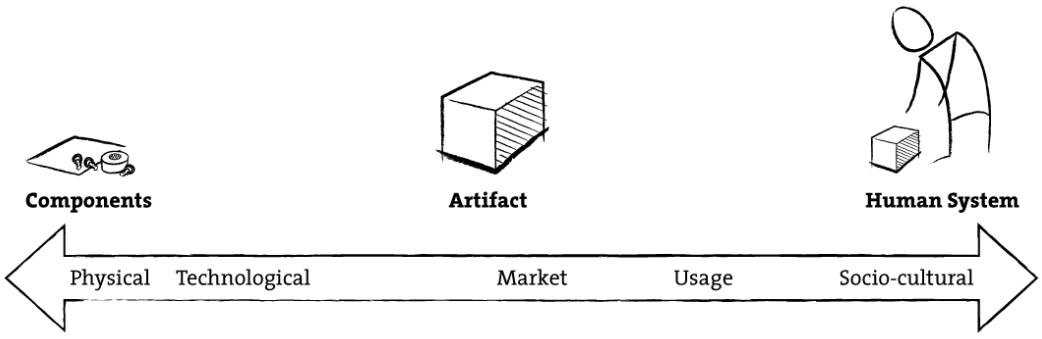


Figure 4.6: The types of constraints that arise typically differ based upon the level of the product system.

Finally, the constraints are decomposed *temporally* as well. The constraints that originate from consumer users (in the future), for instance, are generally addressed independently from

those that arise from the design process (current) or fabrication (near future). Trying to concurrently address the full array of constraints that arise from the duration of the product's life cycle would be next to impossible. Therefore, breaking the constraints down into these temporal categories allows designers to more easily explore and arrange the constraints in a way that more effectively facilitates design activity. In this way, the structure of both the design process—which is broken down into teams focused on different components and different purposes—and the product itself—which is broken down into a hierarchical structure—are the reflection of the nearly decomposable nature of the underlying constraints [55].

It is this concept of near-decomposability, in which the interactions *within* subsystems are more common than those that occur *between* subsystems [27], which allows designers to begin to parse the constraint space—viewing constraints that arise from certain parts of the artifact system separately from others. Breaking a design down in this way can help designers understand, research, and explore complex design problems, as it allows designers to break the full constraint set down into more manageable chunks that can be understood and addressed independently.

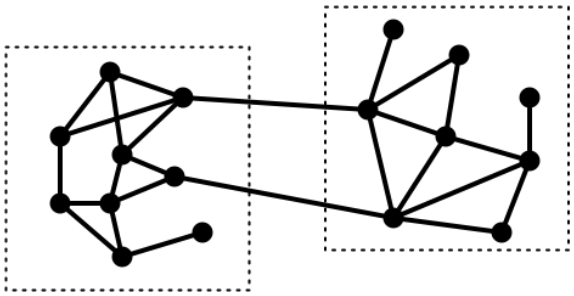


Figure 4.7: Network diagram representing a nearly decomposable set of constraints broken into two more manageable sets.

Given the multitude of constraints that must be balanced within complex systems, it is near decomposability that allows designers to regularly create successful products. Left to deal with all of the interactions and implications of artifact systems simultaneously, design would be almost infeasible. By breaking the constraint space down into successively smaller chunks, designers can focus on balancing increasingly manageable sets of constraints. Once addressed separately, the complete design can be pieced together. Despite the advantages of designing in

this way, sets of constraints can never be isolated entirely and designers must account for the interactions that still exist between these chunks. It is necessary to consider an artifact's use independently from its manufacture, or the sourcing of materials; just as the design of an automobile's engine must be considered separately from the design of the steering wheel. However, designers still need to understand the interactions that *do* exist across these decompositions. These interactions can have large impacts on the design's fitness, and are frequently responsible for unexpected behaviors and failures. Even if every part is designed well (in isolation), there may still be behaviors that only arise when we assemble the artifact and attempt to deploy it in a real world context.

These principles can perhaps be illustrated more effectively using real-world examples. When it was initially introduced in 2001, the BMW iDrive was designed to allow drivers to more easily navigate the vehicle's many on-board systems. The iDrive consisted of a rotating control knob located on the vehicle's console and a dash mounted LCD display. It was intended to provide a single intuitive access point through which users could control the radio, the GPS, and many other computer functions. The iDrive was rolled out to a great deal of fanfare, but once drivers attempted to use it in the car while driving, it interacted poorly with constraints throughout the rest of the system. For many drivers, operating the nested menus while attempting to focus on the road or control the vehicle proved quite frustrating.

Figure 4.8: A first generation BMW iDrive control knob.

As a driver, just imagine performing what one reviewer describes: "Pull the iDrive knob back to select the 'entertainment' menu. Scroll to the bottom of the screen and click 'memory.' Scroll to the top of the next menu and highlight 'AM FM.' Scroll to the right and click 'manual.'

Twist the knob to tune in a station. Click 'memory'—twice—to store it" [192]. This nested interface is certainly not well designed with respect to the current understanding of interface design, but its effects stretched beyond the iDrive itself as the result of interconnected constraints. Everything from perceptions of the vehicle to the public perception of BMW was influenced by the way in which designers chose to address the constraints for this single component. One reviewer notes the iDrive's negative interaction with both the BMW's state of the art sound system (another component), and his perception of the vehicle itself [193]:

> Two thoughts occurred to me as I experienced this [frustration with the iDrive]. First, how ironic is it that BMW has invested all those countless man-hours and untold resources in creating the latest batch of high-fidelity Harman Kardon sound systems, only to pair it with a user interface that makes it nearly impossible to properly adjust the tonal qualities? Second, this has never happened to me in a $20,000 Honda Civic, a $12,000 Hyundai Elantra or a 31-year-old $1,700 Saab Sonnet.

While the iDrive is a good example of the way in which design constraints interact within the artifact, the way in which constraints are handled can also impose and affect constraints in other parts of the system as well. The original Apple PowerBook, released in 1991, serves as an interesting example of how constraints interact within parts of an organization. Prior to the design of the PowerBook, Apple's design for manufacture policy (DFM) was to use no screws. Instead, every Apple product was assembled using snap fits. Because of the constraints established by a laptop computer (size, weight, portability, etc.), the PowerBook was the very first Apple product to move away from the constraints imposed by snap-together assembly, and it was designed with thin walls and positive fasteners—50-75 parts and over 40 screws. However, this computer still had to be fabricated by existing infrastructure that was, as noted by one Apple engineer, "…put there by a different design cycle." When engineers at the manufacturing facility first laid eyes on the initial prototypes, another engineer responded: "You're crazy. We can't build this thing. It has 47 screws in it."

Despite these initial incompatibilities with manufacturing, the PowerBook would eventually go on to be a massive success. During its first twelve months, the PowerBook sold over 400,000 units and generated over one billion dollars in revenues [194]. Its innovative design, ergonomics, and track-pad went on to influence an entire generation of portable computers.

Viewed in another light, however, design decisions made to satisfy constraints in one nearly decomposable part of the system—the PowerBook itself—led to difficulties in another. The introduction of threaded fasteners made the design less fit for manufacturing and assembly. This contributed to significant challenges in ramping up production, backlogged orders, and lost profits. While Apple engineers and designers made no mistake in decomposing the set of constraints in order to focus on the Powerbook itself, they failed to recognize the relationships between Powerbook constraints and those involving fabrication. This lead to a design solution that was less fit to the full constraint space. Although the Powerbook was still clearly a fit design, it is hard to argue that Apple would not have been better off had these constraint interactions been considered and addressed in a different way—possibly through including manufacturing personnel in a more timely way during the early stages of the design.

Producing a design fit to the whole constraint space not only requires analysis at all levels of the artifact, but also requires consideration of the relationships that exist among the many parts of a complex product system. Designers must monitor the constraints related to an individual piece of the design, while simultaneously maintaining awareness of the implications within the full constraint space—understanding how changes to one part of the design affect others. As Alexander notes, a "…good designer keeps an eye on the possible changes at every point of the ensemble…," and must be aware of fitness at, "…several boundaries within the ensemble at once" [4].

4.3.2 Perspective and Constraint Focus Within the Constraint Space

The nearly decomposable nature of the constraint set allows designers to better explore, understand, and address the various constraints that exist relative to a particular design process. There are, however, many possible ways to select a focus and decompose the constraint space. Accordingly, designers must recognize that each decomposition is just one of many possible divisions. Each division reveals new constraints and interconnections, just as it hides other important constraints and breaks connections relevant to the system's performance. This leads to a need to explore alternative breakdowns of the constraint space, as each allows designers to view the design problem in a new way and envision different solutions.

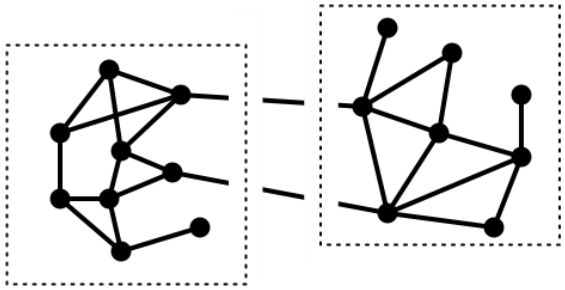


Figure 4.9: Even in nearly decomposable artifact systems, focusing on a set of constraints artificially breaks some relationships.

By shifting perspectives, it is possible to better understand the ways in which a chosen decomposition has affected the designer's understanding. That is, which interactions have been broken in order to view a subset of constraints *as if* they are isolated from the rest of the system. For instance, focusing on the constraints related to a vehicle's engine allows for design to occur more effectively, but also obscures other constraints and interconnections that exist. Alternatively, focusing on the design of the vehicle's interior is equivalent to redrawing the boundary of the design problem. Although, there are still interconnections which exist between these two aspects of the design—engine vibration and noise, for instance—shifting the constraint focus allows for a second perspective within the larger constraint space.

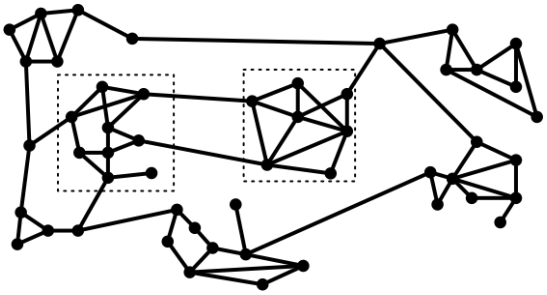


Figure 4.10: Shifting perspectives from one set of nearly decomposable constraints to another still breaks some relationships.

Similarly, designers can zoom into the constraint set in order to better understand a specific part of the design problem. Doing so allows the designers to focus on a limited set of constraints in higher fidelity. Hierarchically subdividing the engine in order to focus on the constraints relevant to a piston, for example, allows the designers to identify constraints not seen

when viewing the system at the level of the whole engine. At the same time it is possible to zoom out, broadening the focus within the constraint space. Focusing on the design problem at the level of the drive-train, or the vehicle and the user, reveals constraints and relationships not visible when viewing the level of the engine. Each of these perspectives is, by itself, insufficient, but by shifting perspectives it is possible to gain a better understanding of the structure of the entire constraint space. By drawing and re-drawing boundaries in this way, it is possible for designers to better understand the full set of constraints on a problem [4], while still providing the focus necessary to actually develop solutions.

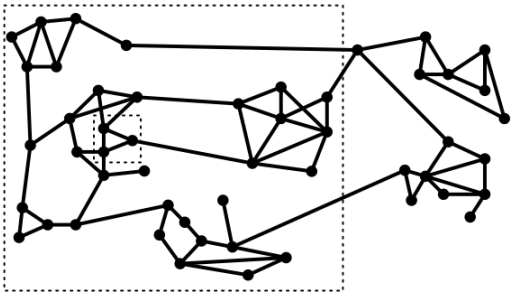


Figure 4.11: Zooming in and out within the constraint space allows greater focus, and a better understanding of the relationships obscured based upon a different constraint focus.

In this way, the hierarchic structure of the constraint space leads to the necessity of exploring the artifact system at all levels. There is no omniscient perspective, and there is no one best view of the constraint space. Rather, by shifting perspective and focus it is possible for designers to develop an understanding of the design problem that is simultaneously deep and authentic. As competing perspectives can lead to a more complete understanding of the system, converging analysis and design efforts from multiple points within the system plays an important role in designing artifacts fit to the constraint space [195].

In many ways, this is an intriguing argument for the value of collaborative and trans-disciplinary design processes. Each designer, from every relevant discipline, has different experiences and skills that ultimately relate to their own particular constraint focus. Just as shifting boundaries within the product system can lead to a deeper and more varied understanding, so too can balancing design processes across these disciplinary perspectives. In order to design products more fit to the larger constraint space, designers must not only include

these perspectives, but also understand where they overlap and where they do not [80]. In doing so, the constraint framework can act as an ideal way to more explicitly recognize the constraints relevant to each perspective, allowing design organizations to better balance these perspectives and their design functions.

4.4 A Changing Constraint Space

The constraint space, like a fitness landscape, is fundamentally non-static. If the constraints on a design never changed, artifacts would, over time, slowly evolve towards some optimal (or locally optimal) solution. Each new product would inch ever closer to an optimal fit with the constraints, just as biological organisms evolve in the direction of optimality for a given ecosystem. This is generally not the case, however, as markets, technology, competition, user demands, and stakeholder expectations change too quickly to allow this for sort of gradual product evolution. Instead, new artifacts, uses, expectations, and contexts characterize the adoption and use of physical artifacts over time. The constraint space against which fitness is judged is constantly evolving; as the world changes, so too do the associated constraints. What was once fit may no longer be so, and the set of constraints for which a product was designed is no longer the one that it confronts.

Products have lives that play out over time and are intricately connected to the lives of the people that use them. Designs come into being at some particular point in time in, under a particular set of circumstances, in order to meet a particular set of constraints. Upon their introduction, they shift and grow alongside their users and uses, creating new constraints and opportunities. Eventually—when they fail to serve a purpose within the now changed field of activity—they 'die' [196]. The influence of the designer plays out within this dynamic context, and the goal of designing for complex artifact systems is to manage the success and longevity of designs within this constraint environment. When a product is released, it has the power to expand user capabilities, change technological constraints, and escape existing archetypes in ways that will forever transform user expectation—not just for itself, but for all subsequently released products as well. In this way, designs are constantly changing their context in a manner which effectively evolves the constraints upon which future designs are founded. This mutually

influential relationship between artifacts and constraints leads to designed systems that behave in ways which are strongly reminiscent of biological evolution [177].

Let us once again look to the example of a DSLR camera to gain a deeper understanding of how artifacts and constraints interact over time in order to drive change, by specifically looking at the way in which a piece of the camera's internal technology (its image buffer) addressed and created constraints at all levels of the camera system. In the first digital cameras, when a user snapped a picture it was written directly to the storage media (compact flash card, SD card, floppy-disk, etc.). This process sufficed for a time, but designers and photographers quickly realized that this structure limited how quickly pictures could be taken in succession: because of the speed at which data could be written to the storage media, a second image could only be taken after the first had been *completely* written. In order to work around this technological constraint on the memory card, digital cameras eventually began to include a 'buffer,' which temporarily stored images waiting to be written. Photographers no longer had to wait for an image to be completely written, and this design feature allowed digital cameras to operate more like their film counterparts [197].

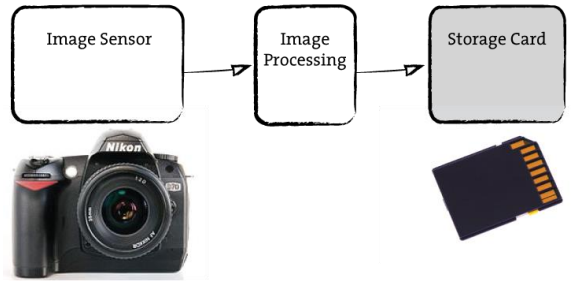


Figure 4.12: The storage card was the limiting component in the workflows of the first DSLR cameras (no buffer).

The camera buffer was an innovation that primarily emerged as the result of technological and usage constraints. The buffer was placed before the storage media in the camera's workflow, and allowed images to queue while they were waiting to be written to storage. The buffers introduction also allowed camera technology advance: image sensors improved, image quality increased, and file sizes ballooned. Alongside these changing technological constraints, higher resolution images, in combination with the many advantages of

'developing' digital images, allowed an increasing number of photographers to begin to migrate from film to digital en masse. These photographers brought with them a host of new usage constraints, desires, and demands. Sport photographers, for instance, demanded not only high quality images, but also the ability to shoot multiple frames per second (FPS).

As the constraint space shifted, the new capabilities afforded by the buffer were soon exhausted. Higher quality images and faster shooting only led to users demanding even greater levels of performance. This is the frequently occurring phenomena in artifact systems, sometimes referred to as the 'law of stretched systems' [191]: stakeholders exploit improvements to better achieve their goals, thus pushing the system to operate near the edge of its new capacities. New design capabilities establish a new baseline for expectations. This, in turn, demands future design improvements, as users desire even greater capabilities. For a while, the buffer was a fit solution, but changing technological constraints (image quality, file sizes, etc.) and increasing user expectations (shooting speed, image quality, etc.) quickly led to a reduction in the buffer's ability to meet ever-greater user demand. In order to address these changing constraints, camera designers began to tinker with the location of the buffer within the camera's workflow.

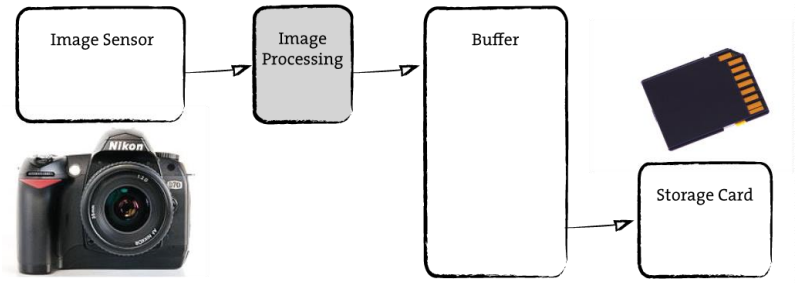


Figure 4.13: The workflow for a DSLR camera with a buffer in the original location [197].

The buffer was originally placed after the image processor. In this orientation, images were processed prior to awaiting storage in the buffer, and image processing quickly became the bottleneck for continuous high quality shooting. This arrangement rendered image quality and shooting speed as competing constraints. As a result, many of the aforementioned sport photographers were forced to reduce image quality in order to maintain fast shooting (as smaller

images can process faster), and not miss what photographer Henri Cartier-Bresson famously called, the 'decisive moment' [198].

To increase image quality and circumvent this trade-off, many camera manufacturers began placing the buffer before the image processor so that RAW image data (from the sensor) was sent immediately to the buffer. This placement meant that shooting speed was independent of the image processing speed. This allowed for more high quality images to be shot in succession, but continually increasing file sizes eventually rendered the buffer as the limiting factor. A user could now only shoot until the buffer was full. This orientation also limited the photographer's ability to affect the speed-quality trade-off: all RAW image data is the same size (changes to file size occur in processing), therefore changing file size no longer affected shooting speed [197]. Looking at this evolution over time, each potential solution (placement of the buffer) addressed certain constraints, and created others.

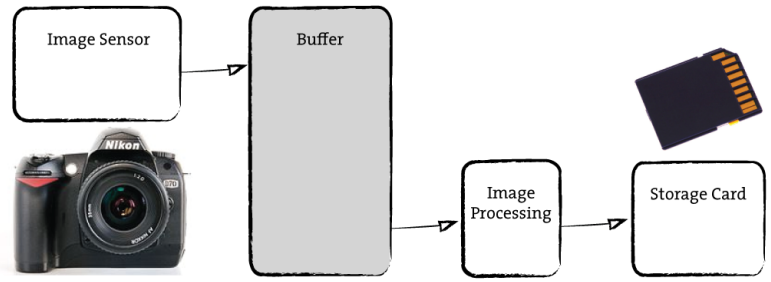


Figure 4.14: Workflow with the buffer before image processing [197].

This was the current state of the constraint space when Nikon began development of the D70 camera. With the D70, however, Nikon designers identified a novel way in which to balance the constraints. Designers developed a 'smart buffering' architecture that combined elements from the two previous methods. As in the 'before image processing buffer,' the unprocessed image is stored in the buffer allowing for a higher FPS. Instead of being written directly to the storage media, however, they are returned to the buffer. In this way, writing to the storage card does not bottleneck image processing, as the processes happen in parallel. Even better, this combined method constantly frees up space for new images, as the images sent to the image processor are larger than those returned (a JPEG is much smaller than the RAW image

data). Just like placing the buffer after the image processor, the images could be written from the buffer to the storage media. This meant that photographers in search of high FPS did not have to wait for the entire burst of frames to be written to storage prior to shooting again [197], [199]. At the time, this novel way of addressing these rapidly changing constraints made the D70 Nikon's best DSLR for burst and continuous shooting—even better than many of their professional DSLRs, which cost thousands more. It also represented an innovative solution within the constraint space that had a lasting influence on subsequently designed DSLR cameras.

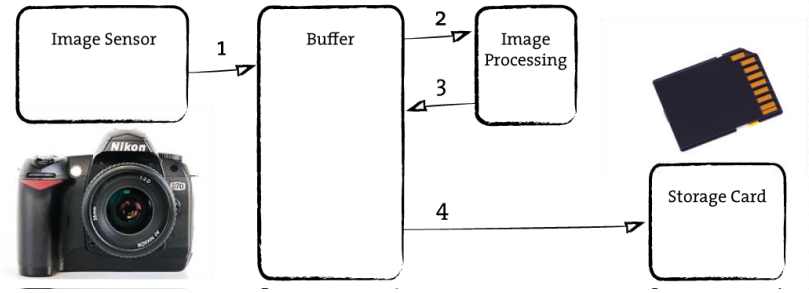


Figure 4.15: The "smart buffering" architecture [197].

While this example focuses primarily on technological and usage constraints, similar behavior can be seen in manufacturing and other supportive technologies. The onset and popularization of injection molding machines, for instance, changed not only how plastic parts could be produced, but also many other constraints. New materials meant new properties that could be leveraged in the context of use; and new manufacturing methods meant new considerations for the design and tolerancing of the plastic parts, sourcing, cost considerations, etc. The evolution of injection molding technology thus changed the constraint space for countless physical products. In a broader sense, new designs are created, which result in new challenges and opportunities. Seen in this way, there is circularity to the processes of design and implementation: "…the world determines what we can do and what we do determines the world" [17]. New products shift the set of constraints, by creating a framework for actions and expectations that did not previously exist. And every artifact—past, present, and future—must contend with this changed constraint space.

Physical products, however, are not the only source of change to the set of constraints: constraint change originates throughout a complex artifact system. Technology is constantly changing, and so are factors such as culture, trends, manufacturing capabilities, etc.; each of these has a relationship to the other constraints on a design problem. Constraints from competitive products, users, socio-cultural systems, technology, etc. are all rolled into a single constantly churning constraint space, against which fitness is judged. In many ways, this leads to coevolutionary behavior, as products help to shape the structure of the constraint space, and the constraint space in turn shapes future designs. Biological coevolution is "…the change of a biological object triggered by the change of a related object…" [200], and each 'object' affects the others' evolution by exerting a selective pressure. In design, every constraint is defined by all of the other constraints on a design problem; changes to one constraint can trigger changes in others.

Even competition between products is brokered through the constraint space, as one product imposes new expectations and constraints on competitive products. Unlike classic predator-prey co-evolution, products do not typically out-compete other products directly. The iPod, for example, did not directly 'kill' the Zune. Instead, it was more fit because it was able to influence the constraint space, resulting in a new set of constraints (shared by both devices) that the Zune was unable to meet sufficiently. Some of these factors may have been related to trends, fashion, and marketing, but there were certainly others related to the product's usage and the systems in which the iPod was embedded. iTunes, for instance, co-evolved with the iPod, and in effect created an entirely new set of constraints and expectations with regard to music purchasing and management, the likes of which had never existed previously. Recall the executive in charge of Microsoft's Zune division who stated that Apple had killed the Zune before it even launched [184]. This was a result of the constraint environment into which the Zune was released.

One sees a similar pattern emerging from the history of removable computer media [79]. Since the introduction of the original 8" floppy disk—designed by IBM to replace tape drives—removable storage media has undergone a series of major make-overs. Initially, floppy disks merely shrunk in size, with a number of 5" variants being introduced before Sony sold the first 3.5" floppy in 1981. Eventually technology improved, file sizes increased, and users desired capabilities that the floppy disk could no longer provide: "The floppy has not been able to keep

up. Applications are doing more. They are generating more data. There is not enough room on a floppy for one song or one photograph from a high-resolution camera" [201]. Eventually, the floppy gave way to higher density disks like the iOmega Zip disk, which was initially capable of holding 100 MB of data—considerably more than floppy disks which typically held 1.44 MB or 2.88 MB.

The Zip disk, however, could not hold its dominant position for very long. It gave way to the recordable CD (CDR), which was better positioned with the set of constraints on removable media at the time. Not only did CDRs have a greater capacity, but they were also compatible with the existing infrastructure of CD-ROM drives, and could be integrated easily into the architecture of laptop devices. In addition, the use of file sharing services and digital music distribution only aided the popularity of the CD, as users were able to 'burn' CDRs playable on CD players and computers. The CD's biggest drawback—its lack of reusability—was balanced by its relatively low cost, and was eventually addressed with rewritable CDs. As time passed and demands increased, other media such as recordable DVDs, re-writable DVDs, and USB drives eventually supplanted the CD-R for many uses. Due to its compatibility with audio devices, however, CDs remained a viable storage medium for music for many users.

Figure 4.16: The evolution of removable media storage.

What changed at each step in the evolution of removable portable media? Was it that the Zip disk was no longer fit to the purposes for which it was designed, or no longer held the required data? No. It was designed to hold 100 MB, and it continued to do just that. What

changed was the environment around the Zip disk: the constraints. Technological and market constraints obviously changed, but so did socio-cultural and usage constraints all throughout the system. Currently, the entire market for removable media is under assault, as electronic devices rely more heavily on digital distribution, digital file sharing, and network connectivity in order to store data, transfer files, and distribute software [202]. External media technology continued to evolve in the direction of greater data density, but the entire constraint space has shifted in an entirely new direction with the advent of 'cloud' computing.

As a result of these uncertain and changing constraints, designers are tasked with hitting a fuzzy, perpetually moving target. Even *if* designers manage to hit the target (or achieve a minimum level of fitness), the constraint environment will undoubtedly change after the product is released. The goals, needs, and expectations of stakeholders are constantly changing as the result of changes to technology, culture, competitive products, etc. Just because a product is currently performing well in the market does not mean that it will continue to succeed in the future. While it may be easy to think about a design's fitness landscape as a relatively static representation, doing so is a gross misrepresentation. In reality, all of the peaks in the constraint space are constantly changing—they are made of sand rather than any rigid substrate. No sooner does a design reach a peak, than does the ground immediately begin to erode out from underneath it.

Figure 4.17: The changing fitness landscape can be illustrated as hills of sand.

This constraint environment, with which design organizations are endlessly trying to keep pace, characterizes the activity of design. This is reminiscent of evolutionary biologist Leigh

Van Valen's Red Queen Hypothesis [203], which states that in a co-evolutionary system an organism must constantly adapt and evolve in order to maintain its fitness to the surrounding organisms and systems. The hypothesis takes its name from Lewis Carroll's *Through the Looking Glass*, in which Alice notes, "Now here, you see, it takes all the running you can do, to stay in the same place." This type of behavior can be seen in 'arms-races' both between and within species [204]. Between species, as the rabbit gets faster, so too must the fox simply to keep pace. Within species, we can look to the example of trees in a forest. In a competition for sunlight, trees grow taller in order not to be overshadowed by their immediate neighbors. Each tree competes to gather the same amount of sunlight while expending greater and greater resources in order to sustain that increased height.

Product markets tend to exhibit characteristics of these arms races: competing designs push each other forward and, at the same time, compete for the same resources within a given market. The forest example is particularly representative of product markets, as continuing development is necessary in order to maintain fitness with the surrounding constraint environment. In each case, the central principle of the Red Queen Hypothesis remains: "…in a competitive world, relative progress ('running') is necessary just for maintenance ('staying put')" [205].

4.4.1 Failure in Complex Artifact Systems

Van Valen originally put forth his Red Queen Hypothesis in order to explain the 'law of extinction,' which states that in a given population, the probability of extinction remains constant over time. This system–level behavior is most readily explained by co-evolution. Adaptations by one species change the selection pressures on another species giving rise to the ever-present threat of extinction. While products do not go 'extinct' in the same manner as a biological species, there is a never-ending string of products that are phased out of the market as new designs are introduced. Newly released products and external factors lead to opportunities that frequently allow for newer designs, more in line with the current shape of the constraint space, to drive older products into obsolescence. As constraints and products interact and evolve, one of two outcomes is likely to occur [45]:

1. *Functional failure:* The design will eventually fail or be unable to perform an intended function as a result of evolving constraints. This includes what are typically thought of as engineering failures—crashes, catastrophic failures, etc.—but also much smaller failures connected to the intended use of a product.

2. *Presumptive failure:* In the face of evolving constraints, assumptions indicate that under future conditions the design, as it currently exists, will fail; or, a different design will do a better job of meeting the constraints. The inability of a cellular phone to allow users to check their email is not a functional failure; rather, users upgrade to smart phones as the result of shifting expectations about what a mobile phone *can* and *should* do. They perceive that a smart phone will better meet their future needs and desires.

As constraints evolve, one of these two types of failure will *eventually* force a re-design of an existing product, or the creation of an entirely new artifact. These dual modes of failure explain why so few designs persist unaltered, even for relatively short periods of time. In the case of cellular phone technology, there is a consistent pattern of failure (mostly presumptive failure) that has led to a procession of new phones, each surpassing those that have preceded it. The average life of a cell phone is approximately 18 months [206]. In spite of how well designed, innovative, and highly lauded the original iPhone was, it was replaced by the iPhone 3G thirteen months after its release.

Figure 4.18: The various models of the iPhone released over a period of five years, from 2007 to 2012.

Even great designs (and those that seem to persist for long periods of time) eventually succumb to evolving constraints. For example, the design of something as simple and seemingly static as the push pin (invented in 1903) has changed as the result of evolving constraints [207].

Evolving manufacturing technology and demanding business constraints have given rise to a push pin that, while looking wholly familiar, is designed and manufactured in an entirely new way. Prior to the onset of injection molding machines, push pin handles were made of glass [208]; as manufacturing constraints changed, so too did the design of the push pin. Further, changes to the pin's manufacturing, along with changing market constraints, have beget design changes intended to increase the speed of manufacture, reduce piece cost, and increase profits. Over a long enough period, almost every design will evolve as a result of new and shifting constraints.

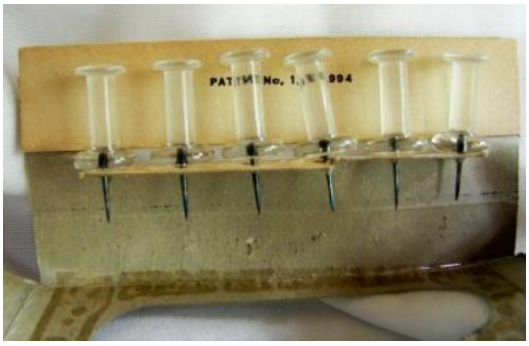


Figure 4.19: The original glass push pin invented by Edwin Moore in 1903.

A large part of the literature on technological and product evolution celebrates successful innovations and successful problem solutions, but as is the case with biological evolution, failures are at least as important. In biological evolution, the importance of failure arises from the fact that the direction of evolution is determined not by the selection *for* successful organisms/genotypes, but by selection *against* those organisms that are not fit to the current environment. Evolution does not select the tallest giraffes, or even those that are the 'optimal' height; it selects *against* those giraffes not tall enough to reach the trees. In the context of physical products, users and markets rarely select the single 'best' solution. Instead, designs which do not justify their continued production (through sales, use, etc.) disappear. In a free market, it is very rarely, if ever, the case that a single product exists in a market segment: even products as dominant as the iPhone will engender competition. There is also considerable evidence that within the design process solutions are developed not by selecting the best ideas,

but by selecting against those ideas which are 'misfit' to the current formulation of the design problem [4].

While there are certainly parallels, the importance of failure in physical products is potentially greater than its importance in biological evolution. In biology, failure is the end of the road for the organism and the genotype; when an organism goes extinct its genetic material is lost forever. In the evolution of artifacts, there is always the opportunity to learn from failure. When a concept or a product 'fails,' it is possible for designers to gain knowledge about the constraint space that can steer future ideas, concepts, and designs to higher levels of fitness and an increased likelihood of success.

It is possible for designers to learn from failure at two evolutionary scales within the artifact system. Within the evolution that occurs across multiple product generations, product failures spawn the search for better, more fit, solutions. Within the design process of the individual artifact, failure can occur at any step in the process, thus contributing to designers' growing understanding. These failures occur when generating and selecting concepts in the 'mind's eye,' as a designer generates a rough idea and quickly tests it based upon cognitive models of the constraint space. They also occur during the various phases of sketching and prototyping [55], [169], [209], with each failure helping to shape future concepts. Failures at these stages of the design process occur frequently and are essential to the development of a fit solution.

From failure, designers can glean a great deal about the constraints most relevant to the execution of a design. Each failure, whether great or small, can provide insight about which constraints are important and how those constraints interact. While it may seem counterintuitive, there is also considerable benefit in seeking out failure within the design process. Rather than waiting for failure to occur in the context of application, pushing designs to failure ensures final solutions that are more fit to an evolved understanding of the constraint space.

It is much more cost effective for failure to occur before production starts, and to identify problems before the design is implemented. Forcing the redesign of an injection mold is expensive and time consuming; a crash in a simulated cockpit is much preferable to the real thing. The sooner designers can identify these failures, the sooner the designs can be adapted in a search for greater fitness. Another major, but frequently overlooked, reason to identify both

functional and presumptive failures prior to release relates to competitive advantage. When failures occur in products that have been released to market, the knowledge gained from that failure is available for all to learn from: this includes competitors. If organizations can push their failures into the design phase, the learning that occurs as a result of failure remains proprietary information.

Because of these factors, designers should consciously strive to anticipate failure prior to release—identifying points in which solutions *will* fail to meet constraints. Whether in their own mind's eye, or by leveraging the expertise of manufacturers or users, designers should be actively trying to push their ideas, sketches, and prototypes to failure. This is one area in which a more rigorously defined constraint framework has value, as it encourages a detailed and holistic approach to the set of factors which determines an artifact's performance. In this way, designers can build knowledge that will be more useful in generating increasingly fit solutions that are less likely to fail upon implementation.

4.4.2 Cycles of Change and Adaptation

Past performance is not indicative of future success. Technology pushes forward. The market, competitors, and users all adapt to changing constraints within the same artifact system. This co-evolutionary behavior leads to *cycles of change and adaptation*. These cycles occur routinely within product systems and give rise to much of the long-term uncertainty associated with product markets. In a series of seminal papers in the late 1980's and early 1990's, ecologist C.S. Holling and colleagues proposed a model of adaptive cycles in complex systems. A stylized representation of this model can be seen in *Figure 4.20*.

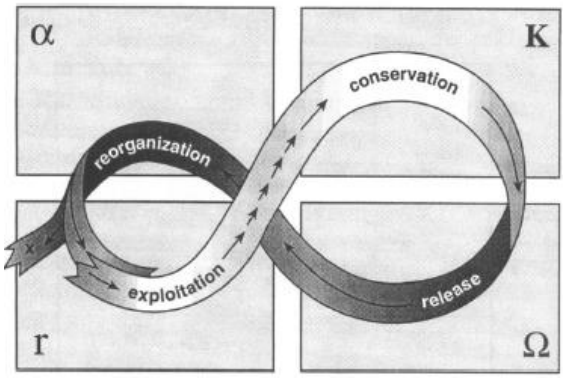


Figure 4.20: Holling's adaptive cycle [210].

This model of an adaptive cycle was the result of many years studying the comparative evolution of ecosystems. Traditionally, ecology focused on movement between phases of growth and exploitation *(r)* and conservation *(K)* [211]. Holling's adaptive cycle included two additional phases—release *(Ω)* and reorganization *(α)*—in order to more accurately describe the behavior of these systems. The adaptive cycle is characterized by two major transitions as it alternates between long periods of resource aggregation and maintenance (from *r* to *K*), and shorter periods which create opportunities for change and innovation (*Ω* to *α*).

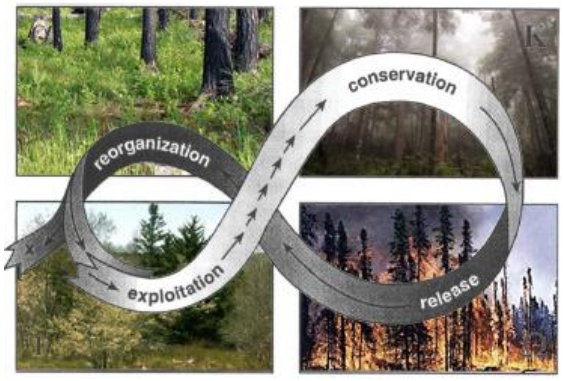


Figure 4.21: The adaptive cycle of a large forest.

The adaptive cycle is perhaps easier to understand in the context of an example taken directly from Holling's work in ecology. Large forests typically exhibit these cycles over long

time periods, characterized by gradual change and abrupt transitions [212]. Following a catastrophic event such as a forest fire, bare ground is quickly colonized by fast growing grasses, plants and shrubs that succeed as the result of quick growth and rapid reproduction (the α *'reorganization' stage*). Eventually trees begin to take root and compete for sunlight—this competition characterizes the *r* phase of the cycle, *'growth and exploitation'*. Over time, these trees grow taller in a competitive race for sunlight, the forest begins to mature, and the system begins to transition to the *K* phase—accumulating greater and greater resources as the biomass of the forest increases. "During the slow sequence from exploitation *r* to conservation *K*, connectedness and stability increase and capital is accumulated." [28]. Over decades, the growth of the taller trees slows as the forest focuses on maintaining its accumulated structure. This transition is marked by a gradual increase in the size and capability of the system, but also in the potential for reorganization.

Once the forest approaches this steady state (the conservation phase) it loses much of its ability to adapt and respond to change, because the resources are controlled by a few dominant species which prevent competitors from utilizing them. As a result, the system becomes increasingly vulnerable to disturbances, or according to Holling, "…an accident waiting to happen." However, any change must be triggered by a specific disturbance—fire, disease, drought, etc. The amount of accumulated biomass represents fuel, which in conjunction with dry conditions and a spark can destroy the existing forest. In this example, the fire represents the disturbance that initiates the release of resources back into the system *(Ω)*. Following a fire, the system reorganizes *(α)* as new plant species take root and the forest begins anew. During this period of rapid reorganization, novelty can "…unexpectedly seed experiments that lead to innovations in the next cycle" [28]. This entire process is what Hollings called the *adaptive cycle*.

Holling himself was quick to note that similar adaptive cycles can be seen in other complex systems, including man–made systems, as well. In the context of product systems, and within an emerging constraint space, a number of products are initially released in which organizations and manufacturers actively seek appropriate solutions *(r)*. This period is marked by an abundance of variation and considerable room for innovation. Over time, however, innovations set the stage for a few dominant designs to emerge. These can be dominant products, or design 'commodities' in which a single product archetype begins to dominate *(K)*.

Eventually, the existing 'stable designs' fail to meet changed expectations, needs, or goals, or the constraint space shifts radically as a result of an innovative technology, product, or user demand. This disturbing event *(Ω)* leads to a collapse, and reinitiates a period of exploration and change, in which new product directions and possibilities are explored *(α)*—ultimately initiating another adaptive cycle.

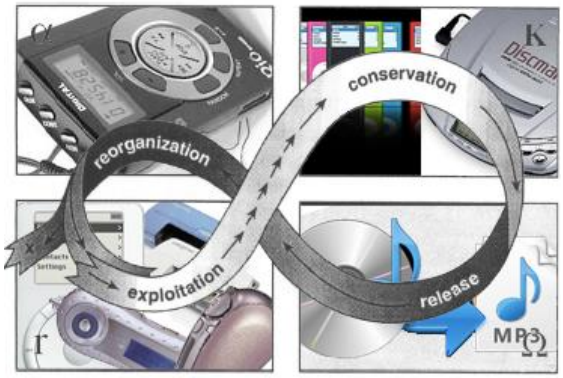


Figure 4.22: The adaptive cycle for mobile music players transitioned from portable CD players to a relatively stable MP3 player market.

In an important paper from 2001, Holling applies his model to a variety of complex systems, both natural and artificial [28]. In this section, we will step through the model in a frame-by-frame fashion, exploring the details of each phase from Holling's perspective, and then applying the model to an actual market segment (portable music players), which will help to ground these ideas.

1. *Potential (that is, wealth as expressed in ecosystem structure, productivity, human relationships, mutations, and inventions) increases incrementally in conjunction with increased efficiency but also in conjunction with increased rigidity. This is the phase from r to K….*

While portable music players existed before the mid-1990s, this example will begin as the portable CD player replaced the cassette tape player as the dominant archetype for portable music reproduction. The cassette tape player had, itself, replaced the transistor radio two decades earlier. The first portable CD player was introduced a year after CDs themselves (which can be

seen as the disruptive technology that lead to the downfall of the tape-player). These new devices, designed around a new and changing set of constraints, offered better sound quality than tapes, easy song selection, etc. [213], and came to dominate the market.

> 2. *As potential increases, slow changes gradually expose an increasing vulnerability (decreased resilience) to such threats as fire, insect outbreak, competitors, or opposition groups. The system becomes an accident waiting to happen. A break can trigger the release of accumulated potential in what the economist Schumpeter called 'creative destruction'* [214]. *The trajectory then moves abruptly into a back loop from K to* ***Ω****.*

Although initially seen as a major improvement, portable CD players began to exhibit signs of weakness as users' expectations and desires stretched. While 'portable,' the devices were limited by the size of the discs themselves and thus were often larger than desired. While the CD technology enabled the user to carry a much larger amount of music than the tape cassette, the disc and player were quite bulky. Additionally, because CD players use a mechanical laser system to read data from the CD, the players were prone to gaps in playback ('skipping') due to jarring or sudden movement of the user. Although this was eventually addressed by improved mechanisms that scanned ahead and played from a buffer, problems of skipping were never completely alleviated. Finally, CD players were limited by the amount of data that could be stored on an individual CD (approximately twenty audio tracks). Although this storage size was initially a positive, it eventually became a limitation. These drawbacks, in combination with a disturbance—the creation of the MP3 audio file format and the onset of digital file sharing—ultimately gave rise to a collapse (***Ω***), and the next generation of portable music players.

> 3. *Innovation occurs in pulses or surges of innovation when uncertainty is great, potential is high, and controls are weak, so that novel recombinations can form. This is the phase of reorganization… where low connectedness allows unexpected combinations of previously isolated or constrained innovations that can nucleate new opportunity.*

The MP3 file format greatly reduced the amount of data needed to store an audio track. As a result the entire system entered into a period of uncertainty, as new modes of playing, distributing, and sharing music were explored. This uncertainty paved the way for a host of digital music players that avoided many of the problems of the previous generation (most notably, MP3 players were smaller and did not skip). Sales started slowly, but within a few years

many companies were producing USB–based MP3 players en masse. However, to this point, the industry had not identified a single dominant archetype, and the market was crowded with a wide variety of differently designed (shapes, sizes, music management software, etc.) players. Within a few years, storage volumes had increased, prices had dropped, and MP3 players had all but rendered the portable CD player obsolete.

4. *Those innovations are then tested. Some fail, but others survive and adapt in a succeeding phase of growth from r to K.*

In 2001, amidst heavy competition in the MP3 player market, Apple released the iPod music player. The first-generation iPods were hard-drive based players and offered an entirely new method of interaction (the innovative click-wheel control ring). The iPod represented the beginning of the transition from *r* to *K*. In time, the iPod would come to dominate the portable MP3 player market—eventually garnering a 78% market share [181]. In order to maintain control and conserve their position within the market, Apple would release a number of generational variants of the iPod—increasing storage, improving the interface, etc.—as well as a number of derivative products such as the iPod Nano, Shuffle, and Touch. This conservation phase has only now begun to release, as media–enabled smart phones are once again changing the portable music environment.

At any given point in time, designs are most likely to find themselves in the *r* or *K* phase of the adaptive cycle, as these are the two longest–lasting stages; ecologists frequently rely on the concept of selection for *r* and *K*-type environments [46]. In *r-type environments*, selection favors "…organisms with the qualities needed to succeed in unstable, unpredictable environments, where ability to reproduce rapidly and opportunistically is at a premium, and where there is little value in adaptations to succeed in competition" [176]. Organisms like weeds and drosophila (fruit flies) are opportunists that perform well in these environments as they can grow rapidly to occupy emerging niches. In new, disturbed, or rapidly changing constraint spaces, innovation and agility are similarly favored. There is a high degree of turnover in these types of *r*-type product markets, as design organizations are still uncertain what solutions are most appropriate for a set of constraints. *R*-type products are those that emerge quickly and rely on innovation, and are frequently evidenced by short product cycles. Rapid innovation, quickly changing

designs, and users who typically purchase new phones every two years, for example, position the cell phone market in the United States as an *r*-type constraint environment.

Figure 4.23: r-type constraint environments change rapidly, and selection favors agility and innovation.

On the other hand, *K-type environments* favor organisms that possess the qualities needed to succeed in "…stable, predictable environments where there is likely to be heavy competition for resources between individuals well-equipped to compete…" [176]. In biology, *K*-selection is thought to favor large size, long life, and small numbers of intensively cared for offspring. Oak trees, Galapagos tortoises, and apex predators such as polar bears are examples. Their efficiency and tenacity help them to hold on to the niche that they have built, often in tight relationships with the other species around them [46]. Consider another example, the internal combustion engine, originally invented by Karl Benz in 1885. As a result of slower and more predictable constraint change, most current automobile engines look very similar to Benz's original internal combustion engine [215]—what constituted a 'fit' engine fifty years ago is still *mostly* true today.

Being in a *K*-type environment, however, does not mean that products do not change. Instead, *K*-type environments are characterized by slower moving constraints that change in a more *predictable* fashion. The automobile engine has not remained static; it has evolved within a slowly moving set of constraints. New technologies and constraints have emerged, but these have been incorporated into the existing design, rather than causing sudden reorganization. At a much smaller scale, the design of the push pin has remained relatively constant because the constraint environment it is designed for has changed so slowly. Manufacturing and distribution have progressed, and the pin has changed accordingly, but the core constraints related to its use have remained relatively static (tacking a page to a wall). Conversely, even in faster moving

constraint environments, there are still conservation phases. The late stage of the MP3 player market—in which the iPod came to dominate as constraint change slowed—represents a conservation phase within what had been a fast moving *r*-type environment.

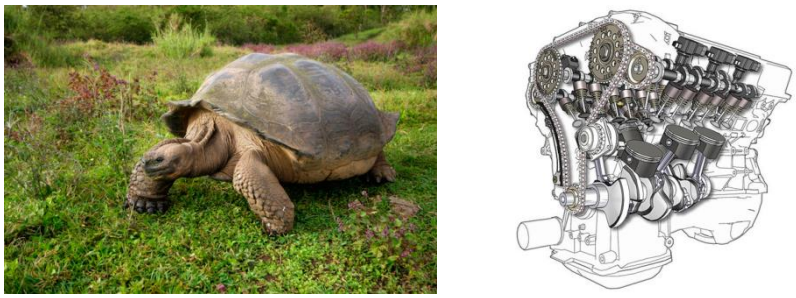


Figure 4.24: K-type constraint environments change more slowly, and selection favors stability and competition.

Clayton Christensen has documented similar patterns of growth and failure in his book *The Innovator's Dilemma* [79]. Fundamentally concerned with the question, "why do well-managed companies fail?" he introduces a failure framework that is marked by what he calls 'disruptive innovations.' He states that the majority of technological progress is due to the development of sustaining technologies, which "…improve the performance of established products, along the dimensions of performance that mainstream customers in major markets have historically valued." This idea is analogous to the more predictable change that occurs in transition from *r* to *K*, and throughout the conservation phase. For a variety of reasons, this growth cannot continue unabated and eventually disruptive innovations will emerge. These disruptive technologies "…change the value proposition in the market… [and] are typically smaller, simpler, and frequently more convenient to use. Therefore they open new markets." Eventually, these disruptive technologies will improve their performance and take over the older markets—quite similar to release and reorganization. Christensen provides examples as diverse as the computer hard drive industry, the hydraulic steam shovel, and steel minimills, to support this argument.

4.4.3 A Joint Strategy within the Adaptive Cycle

Some products are designed to maintain or grow a position within a constraint space, while others seek to explore new constraints and define new possibilities. These are the two principal strategies of both biological organisms and physical products—the opportunist versus the preserver. This is the fundamental "…difference between annual and perennial plants—between weeds like dandelions which scatter profusely to the winds, and dominant species like oak trees, which nurture their few acorns and build an environment that protects the next generation" [46]. Neither, however, is universally successful and there is no single correct strategy. This is reflected in the adaptive cycle as, over time, it alternatively emphasizes both stability and change.

Agile designs are frequently ill–equipped to deal with the nature of competition when the rate of change slows, while more stable designs are often rendered obsolete when they are unable to quickly adapt when changes do occur. Forests are susceptible to fire, and polar bears are seriously threatened by changing temperatures and environments. Even the internal combustion engine appears to be on the precipice of reorganization. Increasing gas prices, oil shortages, emerging technologies, and changing cultural views make it relatively easy to envision a future in which vehicles no longer rely on the internal combustion engine. When the IC engine gives way, engine design will likely move into an uncertain future as hybrids, electric cars, and hydrogen powered vehicles all vie for dominance of an uncertain constraint space.

Long-term survival in real–world constraint environments is not purely about innovation, nor conservation. For a manufacturing firm to remain successful over the long term, it cannot focus solely on reducing margins, increasing profits, and maintaining its current position – as Dell Computer has shown. Neither can it be solely focused on developing innovations and pacing the market. When the constraint space shifts, there is a period of time characterized both by variation and room for exploration. This *r*-type constraint space rewards agility, adaptability, and innovation as these are the characteristics that allow an organization to stay in phase with a rapidly changing environment. Eventually, however, the system will begin to transition to the conservation stage as constraint change slows or becomes more predictable. As the environment shifts into this more stable *k*-type space, a different set of pressures are placed on organizations as a few designs become dominant.

Design organizations and manufacturing firms are not predestined to endlessly repeat a cycle marked by collapse and failure, however. Instead, it is possible for these organizations to compensate for the inevitable changes to the constraint space and to maintain their position [109]. While biological organisms or species can do little to escape collapse and decompensation, human organizations involved in new product design are different. Design is not a traditional ecological system, guided by blind variation and natural selection. It is a *directed* activity guided by human cognition, foresight, and intentionality [54], [62], [82], [177]. As a result, design organizations have the ability to stave off reorganization and spur change by anticipating failures, vulnerabilities, and opportunities.

At the same time, major changes to the constraint space *will* occur, and it is unlikely that reorganization can be avoided forever. Rather than being a helpless victim of these changes, however, it is possible for organizations to push for change—positioning themselves so that they can benefit from it. Further, the choice between maintaining a position and pursuing change through innovation is not a binary one: design organizations have the ability to pursue *joint strategies*. They can simultaneously work to maintain a position, while searching for innovations that will fundamentally alter the constraint space. Doing so first requires the organization to recognize where in the cycle a product is currently located. The adaptive cycle is characterized by two primary environments (*r*-type and *K*-type), and each has specific implications on the design process. The same design strategies that will be successful in *r*-type environments, however, are not likely to be successful in *K*-type environments, and vice-versa.

This difference in strategy between *r* and *K*-type environments is borne out in the difficulty of entering well-established *K*-type constraint environments: despite the significant resources and value (money, customers, etc.) embodied in these environments, it can be very difficult for new product entrants because of previously established positions, competitors, and expectations [28]. The Zune, once again, is a good example. According to Microsoft executive Bach, the Zune was released at the tail end of what was a nearly ten-year run for portable digital music players—just as the market was about to give way to a new constraint environment dominated by mobile smart phones. "If I had hindsight, 20-20, and could do Zune over again, we would skip portable media players completely. We would go to what, at the time, was the Windows Mobile team and say we're going to produce the coolest music service for your phones ever. The portable music market is gone and it was already leaving when we started" [216].

Bach's admittance that Microsoft should have skipped portable music players in order to focus on a music service for phones is a recognition that they were trying to enter a market at the wrong time. His statements, however, also serve as recognition of an alternative strategy. Faced with a difficult–to–enter *K*-type environment, it may be beneficial for new designs to seek to create a disturbance or *initiate reorganization* of the system. Design organizations can consciously search for innovative opportunities and ways to change different parts of the constraint environment: technological R&D, generative design research, exploring alternative problem views, etc. can all be used to identify new directions that have the potential to change the constraint space. These efforts can tilt the scales away from the products dominating the *K*-type environment (iPod), by changing the nature of competition, and initiating the reorganization and exploitation phases. Once in this *r*-type environment, agility and innovation are valued and it is possible to more easily find a foothold. Another example of a difficult to enter *K*-type environment giving way to a faster moving environment, can be seen in photography's transition from film to a primarily digital medium. Film giants Kodak and Fuji dominated a market that was enormously expensive to enter, due to the cost of the chemical plant. However, both were eventually done in by a totally new technology (digital image sensors), which Kodak had helped to invent.

The adaptive cycle is not merely a blueprint for up and coming technologies and organizations. Even companies and products in established market positions are able to pursue innovation and reorganization by utilizing a joint strategy that simultaneously seeks to maintain a position and pursue reorganization. Doing so can carry considerable benefits. Apple, for instance, was able to pursue the development of the iPhone in conjunction with the continued development of the iPod brand. As a result, they were not trampled by the shifting constraints that characterized the move away from an MP3 player market. In many ways, Apple was a major player in this reorganization, but why would they choose to take any action that could potentially destabilize their dominant position? The answer is that once Apple recognized the constraint environment was changing, there were two primary options: hold on for as long as possible, or be a part of the coming change. By initiating and participating in this reorganization, an organization can make itself less vulnerable to it. The iPhone allowed Apple to avoid the negative effects of the reorganization of the MP3 player market, because they helped to define the future of the constraint space. Ultimately they helped to lead the adaptive cycle through a

period of reorganization towards another period of conservation characterized by touch screen mobile phones (similar to the iPhone).

Still, any reorganization of the constraint space carries great risk. While Apple was designing the iPhone, there was no guarantee that a competitor in the fast *r*-type constraint environment would not overtake it. Nor could Apple guarantee that they would be able to accurately identify a fit direction (or design solution) within this new space. The phases of reorganization and exploitation, α and *r*, are highly competitive. Surviving these phases of the adaptive cycle requires agility and innovation, and many designs will fail. Those that do survive into the conservation phase *(K)*, however, will establish themselves in a position to accumulate the fruits of that change. Valuing innovation and pushing the market toward change provides an advantageous position once new markets and constraint spaces have been established. This general pattern can be seen in many product systems, with organizations first focusing on innovation and then seeking to control and exploit that new market [66].

4.4.4 Levels of Adaptation and Evolution

To this point, the adaptive cycle has only been presented at the level of the artifact, but like Brand's layers of change in architecture (discussed in *Chapter 2*) Holling's model actually describes a hierarchic model of change. As the constraint space is also hierarchically organized, change leads to adaptive cycles that play out at *every level* of the complex artifact system. In the natural world, adaptive cycles play out at the level of the cell, the organism, and the ecosystem. In designed products, these cycles unfold at every level of the product and the product system, and they frequently do so at different rates. Like Brand's model there are differing speeds of change within a single product, but these rates are closely tied to the rate of change in the underlying constraints. One level of a product system might be in a fast moving *r*-type environment, while another might be experiencing release *(Ω)*, or in a much more stable *K*-type environment. In a DSLR camera, for instance, the archetype of the camera has remained relatively static since the transition to digital technology, while the image sensors and internal technology have changed dramatically and continuously. It's possible to view the DSLR as being in a *K*-type environment at the level of the camera, and in an *r*-type environment at the level of some of its internal components.

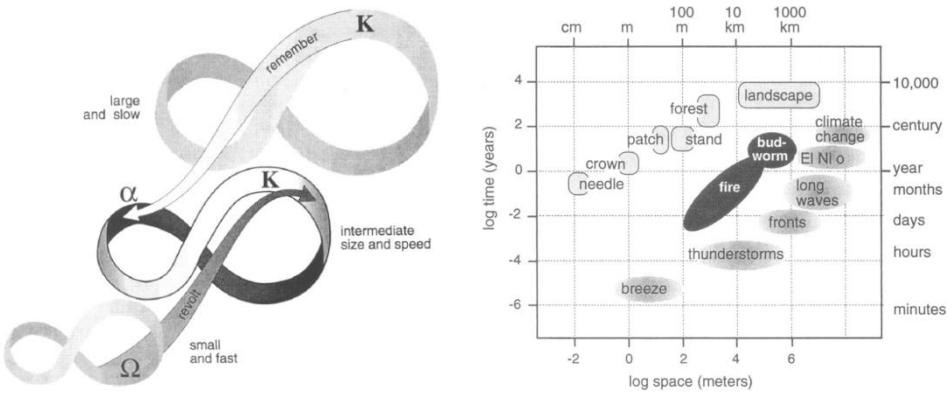


Figure 4.25: Hierarchically organized adaptive cycles, and a hierarchical representation of a boreal forest and the atmosphere organized a long time and space scales [28].

The fact that these different levels of a product can experience different rates of change has large implications for design, because it is the fastest moving constraints that most frequently pace the market and affect future design cycles. In some instances, the technological constraints on a product's internal components may be changing the fastest—as in the case of the DSLR camera. In other instances, market constraints and aesthetics (socio-cultural) may shift trends and drive the redesign of an artifact—as in the case of new model year vehicles, which differ primarily in the sheet metal that is draped around the car's frame.

These nested adaptive cycles are not entirely independent from one another, of course, as "…the adaptive cycle transforms hierarchies from fixed static structures to dynamic, adaptive entities." [28]. As a result of the interconnected constraint structure, changes in one scale will often trigger changes in other scales. However, the nearly decomposable constraint structure also means that these levels can act as a buffer—stabilizing the system in the face of change. This buffering effect occurs in all directions within the hierarchy. This leads to situations in which levels of the artifact hierarchy allow the artifact itself to be both sensitive to change and robust in the face of it. Every new technology does not necessitate a complete redesign of the whole product, as new products and technology are constrained by the slower pace of cultural change and acceptance. Conversely, new uses and expectations are limited by the rate at which products can change to provide new capabilities. The ability of change to propagate through the system is important, but so too is this buffering effect. It allows change to occur relatively independently,

and prevents an artifact system from extremely rapid swings and constant flux. It facilitates design and allows for experimentation on individual parts of the system which encourages evolution and, at the same time, maintains its integrity.

4.5 Challenges and Opportunities

In the design of physical artifacts, context is the source of all meaning. Accordingly, the constraint framework is useful to characterize, categorize, and bring attention to the full ensemble of factors that make up a design's context. Design, manufacturing, and use are all complex activities that designers can never *fully* capture, or model, using the constraint space. As a result, a successful implementation of the constraint framework is characterized not by attempts to fully model the constraint space, but by the development of representations and designs that are *in alignment* with its fundamental structure. This requires an understanding of the constraints and their interactions, as well as recognizing the importance of change.

The design, use, and adaptation of physical artifacts are processes that occur over time. Designing for complex artifact systems is a simultaneous process of adaptation to a dynamic constraint environment and positioning for greater possibilities in an uncertain future [46]. If design organizations wish to be successful over a long period of time, both of these things must occur. Designers, too, must be sensitive to this change at multiple system levels simultaneously. Nuances at the component level are every bit as important as the system architecture and broader design goals, and vice versa. Successful designs inherently address all of the constraint categories at every level of the artifact's design. It is the balancing of details across these levels that leads to products fit to all of their stakeholders and contexts.

To a designer, this unending change at every level of the artifact, and the system, can be a daunting realization. Much like Sisyphus—tasked to ceaselessly roll a boulder to the top of a mountain, only to see the stone fall back of its own weight—designers are fighting an unwinnable battle against constant change. Fighting to design artifacts that are fit to an unknowable set of constraints only to see those constraints change, forcing them to start again. But all is not dire. A slight shift of perspective can lead to a powerful realization: change in artifact systems leads not just to difficulty and failure, but instead to a "…spiral of new challenges and opportunities…" [90]. Designing for complex artifact systems requires designers

to understand and confront changing constraints, but it also presents an endless stream of *opportunities* for exploration and innovation. Changing constraints provide constant challenges and almost certain failure, but changing constraints also mean that design will always have a future because design is inherently *about* the future.

Chapter 5: Design for Change

5.1 Design is Dynamic

Designing successful products is a struggle that involves making tough decisions and balancing constraints under uncertainty, complexity, and change [217]. The effectiveness of a design, meticulously crafted with respect to one set of constraints, can quickly erode in the face of socio-cultural, technological, economic and other contextual developments. The evolution of these factors creates opportunities within markets, altering both what is desired and what is possible. Thus developing designs and organizations that are successful over time requires that designs, and the processes that create them, co-evolve in order to adequately manage change and complexity.

Amidst this background, how can organizations develop products that will perform better in the face of changing constraints? Fundamentally, how can designers manage complexity and change in artifact systems? Designing for complex systems requires designing systems and components whose performance over time is aligned with the demands and pace of their environment. This chapter will discuss two factors that are key to managing artifacts with respect to change: information and product architecture. Information is necessary in order to understand the structure and movement of the constraint space. Product architecture is key because the structure of the artifact dictates how it can, and will, change over time. Together, management of information and architecture can help in designing organizations that will better manage the complexity and change inherent in every artifact system.

5.2 The Role of Information

When examining the definition of 'information', it's surprising to note that a clear consensus has not yet been reached, but the majority of these definitions do not contradict themselves. Rather, the many definitions of information appear to coexist within a larger and

more general understanding of the term. It is possible to initially define information as, "…any fact or set of facts, knowledge, news, or advice, whether communicated by others or obtained by personal study and investigation; any datum that reduces uncertainty about the state of any part of the world" [218]. Looking elsewhere, Edward Tufte states that, "information consists of differences that make a difference" [219]. In his book *Envisioning Information*, Tufte is focused on the design and visual presentation of information, and in this context, these differences can only make a difference when they are *relevant* to the viewer. In the context of Knowledge Management, H. J. Zimmerman defines information as "…goal-oriented collections of data" [220], while T.D. Wilson further defines it as "…data that is embedded in a context of relevance to the recipient…" [221]. By including the term *data* within his definition, Wilson makes a distinction between information and data. Merging these two definitions, it is evident that simple facts, numbers, images, etc. that make up data only become *information* when they are 'embedded in a context' that is relevant to the recipient.

With this in mind, information will be defined here as data that is *extractable*, *relevant*, and *usable* in a given context [8]. In order for information about constraints to be valuable within complex design processes, it must meet these criteria. *Data* is generally the result of observation, action, or experience, and precedes the derivation of knowledge or action. But data must be *extractable* so that it can be viewed, considered, and analyzed. Simply because the data is present somewhere in the system does not mean designers have access to it. Data is only considered *relevant* when it is pertinent to the design of an artifact; it is unlikely that all data is pertinent to all parts of the design. Once extracted, the relevant data must be able to be acted upon—it must be *usable*. This data can be the basis for learning, understanding, action, or any number of other things. Accordingly, data about constraints is only valuable to design organizations if it can be transitioned into meaningful learning or applied within the design process.

Information is relevant to designing for change because it allows designers to construct an understanding of the constraint space for which they are designing; information about each of the five constraint categories is necessary to build a reasonably accurate understanding of the design problem as it actually exists. Information about a varied set of constraints is what also allows designers to identify opportunities and develop solutions that will perform adequately across stakeholders and contexts. This understanding, however, exists both in the minds of individuals within an organization, and in the organization as a whole: this is the primary reason

why design teams must include experts from fields other than design. It is highly likely that the organization possesses information about specific constraints that is unrecognized by or unknown to individual designers. Neither designers nor organizations can ever have *all* of the information relevant to a design problem, as a result of the bounded rationality. Accordingly, decisions about what information to pursue and how to leverage it after it has been acquired are made both consciously and unconsciously.

As a result of the changing constraint space, it is also important to gather information about how constraints *have changed*, and to anticipate about how they *will change* moving forward. As one can imagine, information about how the constraints might change in the future is important for any organization that is thinking ahead to the next several product generations. Information allows designers to not only build a deeper understanding of the constraints that will impact a future design, it also shapes the way in which designers monitor and anticipate change. Understanding the structure of the constraint space and the way in which constraints are changing can help to predict difficulties and open opportunities for innovation. Design teams are thus enabled to more successfully initiate new design cycles, whether revisions, redesigns, or totally new products.

5.2.1 Locus of Constraint Information

In many ways, the design process revolves around uncovering information about constraints relevant to a particular problem or opportunity. This learning occurs as the result of almost every design activity: R&D, design research, and market research are all specifically geared towards identifying, understanding, or altering the constraint space. At the same time, every idea, sketch, or prototype yields information about constraints and their interactions. Even formal and informal conversations between employees and organizational units can lead to the creation or exchange of important constraint information. The ability of designers to learn from others extends beyond the design organization, as constraint information is distributed asymmetrically throughout the product system: users, manufacturers, retailers, service personnel, project managers, etc. all have information that is potentially relevant to the design of a successful solution. This is the reason that design is an inherently inter-disciplinary process, and

it also underpins many research methodologies intended to capture information external to the organization.

In current product systems, there is a fundamental gap between the sources of constraints and the informational needs of designers. This gap must be bridged in order to identify and solve all design problems. Almost all of the relevant constraint information exists somewhere within the product system, but it can be difficult to access that information. For instance, information about intrinsic constraints is often readily available to designers, but information about the extrinsic constraints may be harder to ascertain because it is spread throughout the system. As a result, there is not one central location that holds information regarding all of the relevant constraints. Shifting required information between the locus of information and the locus of design can prove a costly venture; not just in terms of money, but also in time, effort, resources, etc. [102]. Further, some information may be unavailable or unreachable because of the operational procedures, knowledge, or culture of other stakeholders [222]. Designers do not have all the relevant information, nor do the companies, nor do the consumer users. Each stakeholder has only a piece of the total available information. Consequently, developing solutions fit to the full constraint space requires organizations to bring together two factors—problem solving capabilities and relevant information. These two factors must then converge at a single point in the system, at a single point in time in order to most advantageously solve the design problem [84]. This information comes in many forms, and originates from many locations within the product system. What follows is in no way an exhaustive list, but serves to outline a few of the ways in which designers can learn more about the make-up of the constraint space.

Designers can gain insight about the constraint space from the perspective of external stakeholders through both direct and indirect channels. *Indirect stakeholder feedback* can reach the organization in innumerable ways. In today's digital age, this may be easiest to envision as the usage statistics collected by many software programs and digital devices (data-logs, crash logs, browsing data, etc.). This information can provide designers with insight into usage and technological constraints which routinely shape future designs. Indirect feedback is also gathered in other constraint categories as well: for example, information about physical and technological constraints is often gathered by firms in the form of wear patterns, maintenance logs, and repair records. For example, in 1998, Hyundai began offering a ten-year, 100,000-mile power-train

warranty with every new vehicle. In an industry where two year warranties were the norm, offering this unprecedented warranty allowed Hyundai to not only address issues of perceived quality, but also to capture information about the long–term durability of their vehicles that eluded other manufacturers. By extending their warranty, Hyundai captured information about component failure over a longer segment of the car's life, and in turn was able to make adjustments to their designs that would allow future models to avoid some of these problems [8].

Organizations' interactions with stakeholders are not always passive, and they frequently leverage *direct stakeholder feedback* as well. Surveys, focus groups, and consumer interaction are typical examples of direct user feedback in which an organization communicates directly with stakeholders. These stakeholders are most frequently consumer users, but other stakeholders such as manufacturing and service personnel can also be very useful sources of information. In these instances, constraint information is typically gathered through both formal and informal interactions between individuals, as in the discussions that routinely occur between a design group and representatives of an outside manufacturer. This direct stakeholder feedback can occur both during the design process and after a product's release, and both yield important information about constraints and constraint interactions.

Directed research is another way in which organizations can attempt to gather constraint information that originates from other points throughout the product system. This category covers all manner of directed research intended to explore, understand, or alter the constraints on a design problem. It includes R&D (typically focused on technological and physical constraints), market research (market constraints), and design research methodologies such as ethnographic, user-centered, and participatory research (usage and socio-cultural constraints). Each of these types of research is intended to explore constraints in a deep and authentic way, with the intention of identifying potential directions and opportunities, as well as build anticipation about the goals and demands of different stakeholders.

After a product is released, *adaptations by stakeholders* can provide a window into the structure of the constraint space. It is unlikely that designers can ever adequately identify and address every relevant constraint for every stakeholder, and as a result, post-release adaptations to products are common within every market segment. As previously discussed, 'lead users' are those individuals who have needs and goals unknown to the majority of the user base as a result of increased use, familiarity, demands, or expertise. These users are incentivized to make changes

or conceive new applications for products, which can help design organizations to identify previously unrecognized constraints (which may be more prevalent in the future) or completely new opportunities. This early identification about how the constraint space *might* change can be important to the organization's ability to anticipate [223].

To cite a very well–known example, the mountain biking industry emerged in the 1970s as the result of lead users bringing road bikes into increasingly rough and mountainous terrain. This led to a number of changes in the relative importance of many constraints, although these changes initially went unnoticed by the major bicycle manufacturers of the day. Because the industry did not see this major market emerging in front of them, individual users began modifying older "clunker bikes" from the 1950's by adding thicker tires, welding stronger frames, and devising more powerful brakes to address the specific needs that biking on mountain trails created. Eventually, some of these individuals began producing bikes for other riders, and the mountain biking industry was born [102]. This happened in spite of, rather than as a result of, the well–established bicycle industry, because these companies failed to recognize the importance of these emerging patterns of use.

Beyond lead users, all manner of stakeholders adapt their products to better meet unrecognized and emerging needs. When designers recognize these changes as they occur, it is often possible to anticipate major changes both in the constraint space and the market itself. Manufacturing and maintenance personnel, for instance, frequently alter products in ways that can provide information only perceivable from their unique perspective. In any case, these stakeholders and their adaptations can provide information about unrecognized or under-valued constraints not available elsewhere.

Finally, attempts to understand both presumptive and functional design failures are likely to lead to the recognition of previously unidentified constraints or constraint interactions. These learning experiences arise both during the design process itself, and from field trials. If a design concept or prototype fails to satisfy a designer's personal standards, it is an opportunity for learning about the constraint space for example by identifying a previously unrecognized constraint interaction. Designers and design organizations learn from both *failure and success,* of course. This applies to products developed within a design organization as well as designs created by competitors. Astute designers and firms constantly learn from the success or failure of others; it is of course common for one organization build upon a design originally produced by

another. Nikon and Canon did not develop the first digital camera (Kodak did), but they were both able to exploit the value of this emerging constraint space and adapt it to their existing expertise. They gained immensely from Kodak's first attempts at digital cameras and sensors, and were able to learn from their own (and each other's) mistakes and advances, eventually coming to dominate the market for high–end digital photography.

5.2.2 Challenges Associated with Constraint Information

Beyond the sources of constraint information, there are a number of potential challenges that need to be overcome if firms intend to build a realistic view of the constraints on a design problem. First, it is important to recognize that while a few of these information sources can be leveraged before the artifact's design, many of them emerge only after a product has been introduced. Some information about constraints and constraint change can only be acquired after a product's release into the 'ecosystem'. It follows that designers often rely on information gleaned from previous designs and related products in order to build their understanding of the constraint space. This situation leads to a conundrum with regard to the acquisition of constraint information: design requires current and high fidelity information about the constraint space in order to develop fit solutions, but the most current and accurate information about constraints is typically only available after a design has been introduced. Accordingly, the *timeliness of constraint information* is critical. As constraints change, design organizations are tasked with assimilating and applying this information to design problems. In doing so, however, issues arise with fidelity, delays, incompleteness, imprecision and loss in value [224].

Up–to–date information about constraints can be difficult, time consuming, and expensive to acquire, while anticipating future constraints is inherently imprecise. In the face of limited resources, a strategy for balancing dynamic and static constraint information is necessary. Design firms would love to have a precise, up–to–the–minute view of the design constraints, but that is typically not realistic: organizations must make decisions about the constraints for which dynamic understanding is necessary, and for which static information is sufficient. This tension between static and dynamic information often depends on the particular location within the system: dynamic information is most preferable within levels that are changing rapidly, as designers need information reflecting the pace of change. At other levels, the pace of change is

slower, and it is possible to rely on more static information. Simply recognizing which constraint information must be kept current holds great value, as it allows designers to maximize their efforts and get the most out of their limited resources. But even in identifying fast and slow constraints, design organizations must recognize a certain level of uncertainty, as it is not possible to ever fully know which constraints will change in the future. Kodak and Fuji's discussed position within a previously slow moving constraint space is a good example of this uncertainty. These two film giants knew that no other firms were likely to enter their film-based market, but in relying on this they overlooked the digital revolution entirely.

Another challenge associated with building an understanding of the constraint space is *information triage*. When looking at the expanse of constraint information available within product systems, it is immediately obvious that there is a hierarchy of informational importance: each piece of information is not equally valuable. Not only are there relevant and non-relevant constraints based upon the nature of each specific design process, but even within the relevant constraints there are varying degrees of importance. Firms develop strategies for prioritizing the search for constraints, and for categorizing and exploring within known constraints. Simon very effectively conveys this idea: "Information is not the limited resource in these systems, it is our ability to identify and process and absorb useful information…." [38]. Identifying constraints is not a problem within product systems; instead the problem is identifying and imposing only the constraints which are most pertinent to our current problems and decisions. Again, because of the complexity of these systems, it is not possible to devise a single constraint representation that will lend clarity to such a high volume of information. With that in mind, organizations should strive to develop methods, structures, and systems that better allow designers to quickly locate, access, and comprehend the constraints and relationships that are most relevant to their current situations.

In complex product systems dense with information, the *quality and form of information* is also crucial. The quality of information relates to its ability to fulfill the three criteria of relevance, usability, and extractability. This is not a static measure associated with an isolated piece of information. Instead, quality of information is an instantaneous measure that is dependent upon the fidelity of the information as it relates to all of the constraints which define the design problem and the designers' current need. To that end, quality of information can be assessed by observing how well the constraint information facilitates the design activity—the

problem designers are attempting to solve [222]. In the case of product systems, that is how the constraints allow designers to more fully understand and leverage both the design and the system interconnections. The principal idea is that the quality of constraint information affects an organization's ability to effectively carry out design activity, which is closely tied to the form of the information.

Procuring high quality constraint information in a form that is usable by designers is clearly not an easy task. Multiple loci of information, the discrepancies between available information and informational needs, and institutional barriers lead to situations in which design organizations struggle to procure a realistic constraint picture. This can lead to instances where designers adequately address constraints that do not align with the nature of the initial problem [7]. Szczerbicki touches on a number of these points, and even goes as far as to say that the challenge of the next millennium is the management of information [224]:

> Information that is needed often originates at different, geographically distributed sources and is available in different forms and coding. Thus, new tools are needed to cope with this emerging problem of information diversity. The challenge of the next millennium will be to retrieve and transform huge amounts of different forms of information into knowledge needed to support our decision making processes.

Because of the sheer diversity of product systems, it is impossible to identify a single form that information within product systems should, or even could, take. Rather, there is a need to honestly recognize constraints at multiple scales, and attempt to identify some of the general considerations and strategies that will help designers to cope with this problem. The structure of the information exchange between designers and stakeholders must be carefully considered if designers are to obtain a realistic picture of the constraint space. If the constraint information transferred is too shallow, or too little, it may be of no real use to designers, as it does not accurately reflect the system. This, in turn, places an emphasis on the forms of research and inquiry on which a design organization relies.

5.2.3 Leveraging Information: Anticipation and Permanent Learning

Another issue related to the temporal aspects of constraint information is one of timing: "what is better, complete information but heavily delayed, or incomplete information less delayed?" [225]. One might initially think that complete information is worth the wait. But one must also realize that, because of delays associated with collecting and processing, more complete constraint information is not necessarily reflective of current conditions. As a result, any decisions based on more complete information may actually be founded on 'stale' information that is no longer current with the world. For each particular instance, the importance of completeness must be weighed against the necessity for 'up to the minute' information, and a balance must be struck that allows for both sufficient fidelity and a sufficient amount of information.

Accordingly, in order to operate in uncertain and dynamic market environments, design organizations must make *predictions* about the future state of the constraint environment in which their designs exist. Without anticipation, designers are forced to constantly react to the market, often resulting in designs that are considerably off target. Accordingly, information regarding the underlying constraints becomes the key to anticipation—what they are, how they have changed, and how they will change in the future. A view of the constraints grounded in the actual structure of the product system can allow designers to be proactive—anticipating or initiating change, rather than simply waiting for change to occur.

Another strategic aspect of information is the need for *knowledge permanence*. It is necessary to design product systems and design processes with the ability to facilitate the preservation and transfer of knowledge [226]. More specifically, constraint information must be captured and retained so that it does not need to be relearned with each successive product iteration. Simply stated, since designers go to great lengths to understand a design problem, this information should be preserved for future use. It is a waste of resources to 'relearn' lessons and constraint information garnered from previous experience. Knowledge permanence is about being able to transfer constraint information not just from one iteration of a product to future product iterations, but also to unrelated design tasks as well. A deep constraint understanding must be seen as a valuable resource within any design organization. Some of this information is retained within the designs themselves, while other information is retained in the minds and tacit

experiences of the firm's employees. Attempting to more purposefully capture and transfer this information may have considerable value when done in an efficient manner—a well thought–out constraint framework is one step in this direction.

To summarize, the markets for which we design are in constant flux. New products, technology, and information give users new capabilities which will eventually be stretched to their maximum usefulness, resulting in new needs and wants, and further adaptations. For this reason, design organizations must attempt to dynamically capture current and relevant information about the constraints on a design. In addressing these issues, design organizations must first acknowledge their scale, scope, and complexity, by looking to the information distributed throughout the systems in order to gain a more complete perspective. By capturing increasingly accurate information about stakeholders' needs, goals, and contexts—as well as information about constraint interactions and structure—it is possible to generate a more complete system model. Doing so will, in turn, help designers to construct a more thorough understanding of their own perspectives. This can allow designers to cultivate the foresight and awareness necessary to maintain products in highly competitive and unpredictable environments.

5.2.4 Polycentric Information

Two primary concerns of any design organization are to design products better aligned to the needs of their users, and to better manage those artifact systems over time. Accordingly, it is also beneficial to look towards the management of other large complex systems. In this regard, *polycentric governance*, in particular, holds a number of insights that can provide guidance to organizations and designers. The majority of literature focused on polycentric governance comes from economists and political scientists, and much of it is centered on the management of common pool resource systems. In 1968, ecologist Garrett Hardin published his seminal paper, *The Tragedy of the Commons* [227], the title of which referred to the overuse and depletion of a shared resource by individuals acting independently based upon their own self-interest. He argued that this would happen despite a negative result for all parties (a depleted resource), which is contrary to the group's long-term interest. Hardin provided the example of a common pasture, on which multiple farmers are allowed to graze their cattle. Hardin postulated that each farmer, motivated to maximize their own use of the common pasture, would continue to add

cows and graze the land even if doing so would damage the pasture. This behavior would inevitably result in collective overgrazing of the pasture, and the potential collapse of the resource. This scenario embodies both local-global and acute-chronic trade-offs as farmers' actions, primarily concerned with their own benefits in the short-term, lead to costs that are borne by everyone to whom the resource is available.

Since *The Tragedy of the Commons* was published, however, a significant amount of research, most notably in the Nobel Prize-winning work of Elinor Ostrom [228], suggests that real-world management of common pool resources frequently occurs more effectively than Hardin predicted. While Hardin implied that the solution to problems of the commons lay in centralized regulation, Ostrom and others found that successful real-world examples were rarely centrally regulated and relied instead on shared control. These *polycentric systems* have a number of common characteristics, but are most notably characterized by "…not just one but multiple governing authorities at differing scales…," each of which has "…authority to make at least some of the rules related to the use of that particular resource" [43]. At the core of Ostrom's work is the idea that neither centralized nor decentralized systems will perform adequately. Instead, polycentric governance relies on a multi-level balance of control and information, with the understanding that this balance needs to be dynamic across levels in order for the system to function properly [229]. With respect to common pool resources Ostrom states that, "…no single broad type of ownership—government, private, or community—uniformly succeeds or fails to halt major resource deterioration" [217].

Design organizations seek to manage artifact systems in which users, manufacturers, retailers, etc. all have different information, and the ability to control various aspects of the system. As such, design processes that rely on information and expertise from all levels (and parts) of the artifact system are more likely to be successful. Applied to the product design processes, polycentric governance is most relevant in terms of the information present at all levels of the system, and how that information is transferred and applied in order to identify and produce design solutions. With regard to certain constraints and dimensions of a product's design, information coming from a product's users and stakeholders is all but guaranteed to be more accurate and more current than the information that resides with the designers and engineers. For other aspects of the product's design: engineers, designers, or manufacturing personnel may have a more relevant view of the product system. At the same time, most

individual stakeholders lack aggregate information and the 'big-picture' view of the larger system, and designers (or the design organization) are thrust into a central role responsible for balancing a holistic set of constraints.

Completely centralized design processes—in which designers are reliant on their own perspectives, understanding, and envisioning—are every bit as likely to be misaligned to the actual constraints on an artifact as the views of a single user. This implicit realization has led to the introduction and wide-spread application of user-centered design methods, as well as more contemporary research methods such as applied ethnography and participatory design. These design research methods attempt to investigate users' perspectives and constraints in increasingly deep and varied ways [21]. Further, there also exists design activity not conducted by organizations or central designers. Lead-user [102], crowd-sourced [230], and open-source development processes have a closeness to the problem that design organizations do not. But these decentralized design initiatives often do not possess the skill, time, or tools necessary to produce successful artifacts. These initiatives frequently represent a very tight perspective on the constraint space, and are therefore more likely to develop locally adapted designs that perform well for a subset of the constraints only, rather than for the full constraint space against which design fitness is judged. There may also be a tendency to focus on acute rather than chronic goals, leading to a system that is less temporally fit—prioritizing the current constraints in favor of future challenges and opportunities.

In essence, polycentric governance suggests that the design processes most likely to develop fit solutions are those that can best balance different aspects of each of these methodologies. Doing so can allow designers (whether organizations or individuals) to build a picture of the constraint space that is as authentic as possible with respect to a wide selection of relevant factors. Polycentric governance stresses the value of taking multiple perspectives in order to manage the conflicts that exist between designers' understandings and the goals and needs of the stakeholders, who are actually present within the ongoing field of activity. Accordingly, local information and knowledge, from a wide range of stakeholders, must be balanced with respect to the high-level goals and directions of the design organization. These differences in perspective and information are integral in leading to a more complete account of the larger system, and must be incorporated into design thinking [195]. Design organizations are likely to benefit from the application of a wide variety of design methodologies and research

techniques. Each provides a unique perspective on the constraint space, so long as they can combine and balance these perspectives in a way that benefits exploration and execution. Structuring research and design activities in this way will allow designers to avoid local-global trade-offs and stay in closer alignment with the way in which the constraints on a design are actually changing.

5.3 The Role of Product Architecture

Information about the constraint space and how it is changing is critical to design. Once this information is recognized, the physical nature of the product itself often limits an organization's ability to change in step with the constraint space. In complex artifact systems, it is important to be able to monitor both the artifact and the constraint environment, but that information is of limited value if design organizations are unable to act upon it [90]. Designing for change stresses the ability of organizations to develop artifact structures that are designed with ongoing change in mind, and able to adapt in the face of it. Because the influence a product's structure has on limiting, enabling, and directing change can be profound, this section is devoted to exploring the role of product architecture in designing for dynamic real-world systems.

The role that an artifact's system–level structure, or architecture, plays in its performance and adaptability is not a new concept. In his 1969 paper on the development of an extendable computer operating system, Butler Lampson—renowned computer scientist and founding member of Xerox PARC—laid out the case for considered and flexible system architecture [231]:

> If a system is to evolve to meet changing requirements, and if it is to be flexible enough to permit modularization without serious losses of efficiency, it must have a basic structure which allows extensions not only from a basic system but also from some complex configuration which has been reached by several prior stages of evolution.

A design environment characterized by changing constraints places unique demands on the structure of a physical product, and the design of a product's structure has implications for

its ability to change, explore alternative directions, and facilitate learning. Within the design of physical artifacts, this structure is frequently referred to as product architecture.

5.3.1 Defining Product Architecture

In design literature, *product architecture* refers to the internal, system–level structure of a designed artifact. There is no cohesive theory of architecture [90]; definitions and critical features vary from author to author. This section will not attempt to cover all of the viewpoints: rather, it will look to build a generalized definition of architecture that can span disciplines and serve the exploration of designing for complex artifact systems.

One of the most widely cited definitions of product architecture can be found in Ulrich and Eppinger's, *Product Design and Development* [6]. They define product architecture primarily in terms of an artifact's functional elements and physical parts. The purpose of a product's architecture is to define a design's basic physical components in terms of what they do, and how they interface with one another. They note that every physical artifact can be thought of in functional as well as physical terms. The *functional elements* of a product are those responsible for specific operations and actions. For a camera, these can be things such as 'open shutter,' 'adjust aperture,' and 'capture image.' These functional elements are specified early in the design process. On the other hand, the *physical elements* of a design are the parts, components, and assemblies responsible for actually performing the product's functions. Sometimes, the physical elements of a product are determined by what the over–arching design goal is—deciding to design a digital camera, for instance, necessitates an image sensor. Other times, the physical elements depend on the execution, and are defined in an attempt to best fulfill emerging constraints.

In physical products, the physical components of a product are typically organized into what Ulrich and Eppinger call 'chunks.' While 'chunk' is a frequently used term, these elements are also referred to as modules, or modular components. The chunks break a product into a collection of physical components, which then implement its functions. Ultimately, "the architecture of a product is the scheme by which the functional elements of the product are

arranged into physical chunks and by which the chunks interact" [6]. It is this connection between functional elements and physical structure that underlies 'product architecture,' and these mappings are frequently system-level decisions made before the actual components are designed.

Modularity and integration are two of the most important aspects of product architecture [6]. Accordingly, these concepts require a more detailed understanding, specifically in how they affect design and performance. *Modularity* refers to the degree to which a product's elements are split up and assigned to different modules, or chunks, in order to facilitate design according to a formal architecture [232]. Modularity, though, is best defined in contrast to *integration*. The most modular architecture possible is one in which each physical chunk represents a single functional element—one function, one chunk. Integral architectures, on the other hand, have functional elements that are typically spread across many discrete components, and a single chunk may incorporate many functional elements. In other words, one chunk, many functions; or, one function, many chunks. As a result of the difference between these two core architectures, the interactions between modular chunks are typically well defined, whereas in integral architectures boundaries between functional elements may be difficult to identify or non-existent [6].

Figure 5.1: The highly modular Swiss Army Knife in contrast to a highly integrated multi-tool card.

A product like the Swiss Army Knife is typically thought of as possessing a highly modular architecture, as it contains a number of discrete tools, each representing a specific function. In direct contrast are a number of highly integrated multi-tools that have been designed

for extreme portability. Many of these tools have been designed to be roughly the size of a credit card so that an individual can carry it with them wherever they go. In an attempt to fit the functionality of a Swiss Army Knife into a wallet, these tools group a number of functions onto a single piece of metal. These two tools address a similar set of constraints in very different ways. They differ not in the functional elements that they contain, but rather how those functions are grouped: in other words, in their architecture. The Swiss Army knife spreads those functions across relatively independent components, whereas the multi-tool card aggregates all of those functions into a single highly integrated component.

Consider the differences between the architecture of a desktop PC and a laptop (covered briefly in *Chapter 3*). In many important ways, these two devices have essentially identical constraints, in terms of 'computing performance'. The laptop has one additional constraint: that it be as portable as possible. This single constraint leads to a totally different product architecture. In order to reduce size and weight, laptop computers have been forced to integrate many of the components that are highly modular in desktop PCs. The desktop PC has clearly defined modules, with each specific module serving a specific functional element of the design: the hard-drive stores information, the CD-drive reads optical disks, and the graphics card improves visual performance. This high degree of modularity extends outside of the desktop's case as well: the monitor is its own chunk, as are the keyboard and mouse, each with clearly defined functions. These modules all interact through highly standardized interfaces.

In contrast, a laptop, or even more extreme, a tablet computer, is highly integrated. To provide portability, a tablet has many of its internal components integrated into larger and increasingly complex chunks that each performs multiple functions. In an Apple iPad, for example, the graphics processor is integrated into the microprocessor rather than being included as a separate graphics chip. This plays a key role in the size reduction and power draw of the components [233]. Many other components—the hard drive, CPU, and gyroscope—are integrated by being soldered directly onto the mother board. This extreme level of integration is mirrored in how the machine is used. The monitor, keyboard, and mouse (for viewing and interacting with the computer) are no longer separate components. Instead, the iPad's screen integrates all of that functionality into a single chunk: the visual display and input devices (the keyboard and mouse are both replaced by a capacitive touch screen)—one component, many functions.

Figure 5.2: The highly modular desktop PC is contrasted by the highly integrated tablet computer.

This example also illustrates the primary benefits and drawbacks of both extremes of product architecture. Because the functional elements are largely isolated and self-contained, modular architectures allow for components to be changed, replaced, or upgraded both by users and manufacturers. With a desktop PC, users can easily replace a failed power-supply unit, or upgrade the processor to achieve greater performance. This can carry significant benefits, but also requires that design organizations develop the interfaces (physical, energy, information) necessary to support this modularity. As each modular component must have its own structure and interfaces, modular architectures also tend to sacrifice performance in comparison to more integrated architectures.

Because of the tight coupling between both physical and functional elements, integral architectures frequently have the ability to achieve levels of performance that modular architectures are unable to obtain. Whether performance is judged with respect to size, weight, efficiency, or feel, integral architectures are frequently seen in highly demanding or constrained contexts. This is the reason integration is frequently seen in high performance objects ranging from spacecraft to sporting goods [6], [155], [234]. The high performance demanded (per unit of size and weight) is the reason that tablet computers, and other portable electronics, have taken on highly integrated architectures that tightly knit functional and physical elements.

The desktop PC also serves to illustrate the important point that very few physical products are either entirely integrated or entirely modular [235]. Rather, almost any artifact of any complexity possesses both modular and integrated systems, sub–systems, and components, depending upon the level at which the system is viewed. With regard to the desktop computer,

it's possible to decompose its architecture in increasingly detailed ways. The PC can be seen as a highly modular system architecture that possesses a high level of integration at the sub–system level: the hard drive, the motherboard, and even the keyboard are all highly integrated components in their own right. Even the highly modular components of a Swiss Army Knife occasionally integrate multiple functions: the end of the can opener tool, for instance, is designed to also be used as a screwdriver. These examples demonstrate the hierarchical nature of product architecture, and the integration that exists within most modular components.

5.3.2 Product Architecture's Underlying Structure

The ability to break complex artifacts into chunks in order to better design and study them is a direct result of the previously discussed properties of hierarchy and near decomposability. "Every object is a hierarchy of components, the large ones specifying the pattern of distribution of the smaller ones, the small ones themselves, though at first sight more clearly piece–like, in fact again patterns specifying the arrangement and distribution of still smaller components…" [4]. This breakdown is reflected in the architecture of physical products, as well as in the systems responsible for the creation of these artifacts.

This hierarchic and modular structure arises naturally from the interactions of the design, the problem, and the design process [64]. As designers develop an understanding of the design problem, it is possible to decompose it into various functional elements and sub-problems. With this decomposition in hand, designers can structure the design activity, which in turn begins to define the architectural breakdown of the product's physical chunks. In this way, there is a natural symmetry between the structure of the problem and the architecture of the product, as the act of design naturally imposes a hierarchical and modular structure on the artifact itself [4], [54], [55].

A product is comprised of a mixture of components, some of which are relatively independent (exerting little influence on another) and some of which are tightly coupled [236]. Modular chunks tend to possess a high degree of intra-component coupling. In these modules, interactions are numerous, and design decisions (changes to one element within a chunk) frequently lead to a simultaneous change to the other elements within that chunk [16]. This tight coupling, however, does not exist across all of the components that make up a design. Within a

product, there are also functions and chunks that are more loosely coupled with one another. These lesser-connected elements allow the product to be broken up into modules with a comparably low number of interdependencies with other chunks. This is nothing more than the practical application of near decomposability, but it is extremely important as it allows designers to impose structure on the system.

The behavior of each module is approximately independent of the other modules, and the modules are interdependent only in an aggregate way [27]—for example, the desktop PC's monitor can be viewed as nearly independent from the rest of the computer. Because it is connected only by a single cable, it is only dependent on the aggregate functioning of the PC. The internal machinations and processes of the hard-drive have no effect on it. This simple example can help to illustrate a number of potentially beneficial effects of appropriately defined modularity.

First, modularity makes many design activities more manageable [236]. By allowing the product (and the product system) to be cognitively broken into loosely-coupled modules, designers can more effectively understand and design for one part of the product. Modularity can (effectively) remove the noise associated with simultaneously considering *all* of the constraints on an artifact. This allows designers to research and explore the constraints relevant to a single chunk in a far deeper way. Typically, these modules are small enough to be understandable as a single unit, but large enough that designers must still balance a meaningful number of constraints. Designing a modular chunk is typically not a trivial activity, but it is much easier than attempting to simultaneously tackle the entire design problem. Attempting to design a computer monitor, is a more tractable problem than designing the entire computer system, just as designing the monitor's screen or control interface (themselves modular components) is a more practical activity than designing the whole monitor. This facilitates more effective understanding, design, and *evaluation*. Rather than judging the fitness of the entire computer system, it is possible to evaluate the monitor independently from the rest of the computer; or the monitor's user interface separately from its display or its physical form.

Defining the design problem from this narrowed perspective makes it much more conceptually accessible. This permits designers (or teams) to develop separate chunks of the product sequentially or concurrently [6], [235]. The monitor's screen may need to be designed prior to its physical housing (sequential), as the product of one process imposes constraints and

produces outputs necessary for another. In other instances, the computer's monitor can be developed in parallel with the rest of the computer (concurrent), as these two modular components are relatively independent of one another. This effect of modular architectures can make design projects, large and small, easier to manage and control. It can also greatly reduce the amount of time necessary to develop a complete product [237].

Once fabricated, the physically distinct nature of these modular chunks provides advantages to stakeholders throughout the artifact system. Diagnosing problems in modular products is typically easier than in highly integrated ones. Suppose that an individual presses the power button on their computer, but instead of the display lighting up and displaying information, the screen remains blank. If the computer has an integrated display (as in a tablet computer), the source of the problem can be very difficult to diagnose: is the display broken, the video card defective, or the operating system (software) malfunctioning? If the display is a modular component, determining if the problem lies with the monitor or the computer is as simple as changing out the monitor. If a second display works, the monitor is broken; if not, the problem lies within the computer. Modularity also makes components interchangeable. This makes maintenance and replacement easier while allowing products to be more easily upgraded to expand capabilities or improve performance. If the monitor *was* the faulty component, the user has the option to replace it for the same model, or to purchase a newer model that is larger, sharper, or more energy efficient.

Further, modularity holds potential benefits for design organizations with respect to the utilization of resources. Some modules can be designed in such a way that they can be reused in other parts of the design, other products, or future design processes. This allows for the leveraging of existing manufacturing resources (tooling, machines, etc.), as well as design efforts, thereby achieving significant economies of scale across product lines. Design efforts do not have to be duplicated over multiple projects if an identical modular component can be used. This facilitates the development of 'families' of products which share like components, and expanded manufacturing capabilities like 'mass customization'—the mass production of individually customized goods [238]. If a single modular base can be developed, it can be leveraged across a range of monitor types and sizes. This means that a new base does not need to be designed for every new monitor; nor does new tooling need to be designed. This standard base can also be

used to unify the aesthetics across a range of products, establishing uniformity across the brand (or product family).

Although decomposing a product into modular chunks has many benefits on the design process (designers can focus their efforts on a single module, for instance), designers must be aware of the interactions that still exist between modules. Accordingly, designers need to ensure the performance of the full product once the individual modules are re-aggregated. This requires a focus on the interdependencies across modules, as well as the design of interfaces between individual chunks. The interactions that exist among modular components are crucial to the performance of the artifact, as well as within the design process itself. These interactions exist on a continuum from well recognized to completely unknown. Ulrich and Eppinger recognize two primary categories: fundamental interactions and incidental interactions [6]. *Fundamental interactions* are the critical interactions between chunks of the system that define its functionality. They are well known, well understood, and are deliberately designed into the system. *Incidental interactions* on the other hand, are those interactions that do not define the critical relationships between elements, are often unknown, and often emerge unexpectedly, and unavoidably, out of the performance of the entire system.

The fundamental interactions are easier to plan for and often drive the development of interfaces between an artifact's modular chunks. The presence of these known fundamental interactions allows designers to map the system at a high-level, and more easily specify the interfaces and protocols between chunks. In the design of a tablet computer, the fundamental interactions are the known flows of information and energy that exist between the display and the rest of the device. The device outputs information that must be sent to the screen to be visually displayed. At the same time, the screen senses information input by the user that must be transferred to the device in order to produce an appropriate result (open a program, type a letter, etc.). These known interactions determine the structure of the interfaces and communication protocols that define the functional relationship between the display module and the rest of the tablet.

While fundamental interactions are critical to defining the product's architecture, the incidental interactions are still quite important, as they are frequently the cause of emergent problems, breakdowns, and errors. These are the interactions and relationships between components that are frequently unrecognized and unplanned for. If heat from the tablet's

processor were to reduce the life of the display, this would be considered an incidental interaction. At the same time, these incidental interactions can have positive effects as well. Unplanned for synergies and interactions have the potential to lead to new understandings and capabilities after the artifact's introduction. If these potentially positive interactions can be recognized prior to release, they can represent leverage points that can be explored for potential innovation. As these incidental interactions are not critical to the designer's decomposition of the system, however, they are not typically central to the way in which interactions and protocols are specified.

Together, *protocols* and *interfaces* specify the physical and non-physical rules for the configuration and interaction of a product's components. As each of the interconnected modules must adhere to these rules, designers frequently impose them through the introduction of constraints on two or more separate chunks [91]. In a DSLR camera, for instance, a single physical interface is specified for all of the camera bodies and lenses made by a specific manufacturer. This ensures that a range of modular lenses, designed separately from the camera body, will fit—affording flexibility in design and use. For Nikon cameras, every lens produced since the introduction of the Nikon F 'bayonet' lens mount interface, in 1959, must fit every Nikon SLR camera—both digital and film. Those same Nikon lenses will not fit a Canon body, however, as they have different physical interface.

Interfaces and protocols are often maintained over many product generations. In 1986, Nikon introduced autofocus lenses. This innovation allowed the lens to be automatically focused by the camera body, rather than the photographer's hand. These new autofocus lenses were still usable on older Nikon cameras because the existing interface did not change, but the autofocus feature could only be taken advantage of by newer camera bodies with an additional interface. In this case, the new interface consisted of a tiny motor (on the camera body) that mated with a small focus screw on the lens. Eventually, Nikon began producing lenses with computer chips in them that were intended to meter distances and light levels. These new technologies were incorporated by the inclusion of yet another new protocol that allowed electronic communication between the camera and the lens [239].

Figure 5.3: The Nikon 'bayonet' lens mount, and the auto-focus screw on Nikon AF lenses.

Each of these interfaces was defined by their fundamental interactions, as these are the *specified* interactions between the lens and the camera body. Incidental interactions, on the other hand arise because of the implementation of the chunks, and are frequently more difficult to recognize and anticipate. Vibration, or thermal expansion, originating in one chunk that affects the performance of another module can be seen as an example of an incidental physical interaction [6]. These incidental interactions can also occur along other dimensions, or emerge over time as constraints and artifacts change. In the case of the DSLR camera, many of the newer computer controlled lenses are considerably larger than their older counterparts. When placed on older camera bodies, these lenses can block some of the camera's operational controls, making it difficult for users to access all of the camera's capabilities.

Figure 5.4: Over 50 years many features have been added and the physical form has changed, but the mount itself is mechanically identical, allowing either lens to be used on the original Nikon F film cameras or Nikon's newest DSLRs [240].

Although the Nikon lens and the camera itself have evolved considerably over the last fifty years, the original interfaces and protocols have been maintained. This has allowed Nikon to build a highly adaptable portfolio of technologies and products. Interfaces and protocols

preserve the rules of interaction, and are therefore a crucial piece of the artifact system that persists over time. Accordingly, these elements may actually be more fundamental to the system architecture than the modules themselves. This is because the modules can change and diversify only insofar as they obey the rules of interaction established by interfaces and protocols [91]. In this way, shared interfaces and protocols provide a *platform* for modularity, diverse functionality, and scalability that facilitates the variation necessary for the development and evolution of modular products.

5.4 Architecture as a Path–dependent Plan for the Future

Product architecture primarily concerns the intersection of functionality and structure, but the influence of architecture stretches beyond the product itself. A product's architecture intersects the constraint context, the stakeholders, and every on-going field of activity. Accordingly, designing a product's architecture is fundamentally about making choices that give rise to the organized structure of the *artifact*, which also impose hierarchy and modularity on the *entire system* [90]. This structure subsequently shapes not just the structure of the artifact itself, but also the subsequent design activities as well as the artifact's performance in the context of use. With this in mind, it seems advantageous to view *product architecture as a plan*. This 'plan' is frequently unrecognized, but it nonetheless plots the design's course through the design process and the world, long before the design itself is ever finished.

The design of a product's architecture is partially directed in order to achieve a certain set of goals and objectives, and partially emerges from the design process and the structure of the problem [6]. In reality, few architectures have every component and relationship explicitly delineated from the beginning, just as few architectures emerge without any consideration for its consequences. Instead, previously established architectures coupled with the experiences of designers and organizations consciously and subconsciously predispose certain functional hierarchies. In this way, product architectures can be seen as *path dependent*: the design of current and future architectures depends on what has been done in the past. History—in the form of previous architectures, understandings, and relationships—is embodied within a product's architecture, and is necessary to explain how a product and its architecture came to be [17], [59].

In biological evolution, path dependency is a result of an organism's previous evolutionary steps, and constrains how it can evolve in the future. In every generation, random mutations change some part of the organism's 'design', very often in ways that are harmful to survival. It's important to note, however, that organisms can only evolve along the vector of evolution that they have been travelling. A turtle cannot simply evolve wings because it will make it more fit to its environment, as its evolutionary direction is constrained by the mutations that brought it to its current state. Its future direction is dependent upon its previous path. But path dependency means much more than the simple fact that 'history matters'. Small changes to a product's architecture in one generation can lead to highly divergent (and unforeseen) differences in the future. In the design of a product's architecture, previously existing architectures frame and direct future design decisions. Thus, the design of future architectures "…can become narrowed around the dimensions and structure of the previous design[s]" [78]. The architecture of a fourth-generation derivative product is dependent upon the architecture and constraints of the third-generation product, which is a function of the second generation, and so on. As each is dependent upon the 'starting point' supplied by the previous generation, changes to any of the designs in this series are likely to result in future architectures that look fundamentally different [12].

History and pre-existing structure predispose new designs to certain architectures, but unlike the case of biological evolution, designed products are not entirely limited by their histories. The act of design itself implies the ability to escape path dependency, as design is a directed activity that leverages human creativity and ingenuity in the pursuit of innovative solutions. Questioning the reasons a product is structured in a particular way, exploring multiple perspectives, and consciously searching for more promising product decompositions can all lead to innovative design directions and products more fit to the current and future states of the constraint space. While it is never possible to fully escape history, new architectures can allow designers to break from the current path, thus defining a new plan that can confer significant benefits to every part of the system.

While every product has an architecture, not all architectures are explicitly 'designed': many architectures emerge without conscious intent on the part of the designer. Whether expressly designed or not, the product architecture will influence a host of factors related to the product's design, manufacturing, and use. This section makes explicit some of the factors that

contribute to the path dependency of product architectures, and explores some of the benefits of consciously designing architectures that are in alignment with the constraint space. The *factors influencing architecture* are intended to help designers understand the factors which may predispose them in the direction of certain architectures. The factors for which *architecture defines a plan* are those most likely to be influenced by architecture. By making these factors explicit, designers are increasingly likely to question a product's architecture, and its fitness for a particular set of constraints.

5.4.1 Factors Influencing Product Architecture

An early factor which can influence product architecture is the underlying *structure of the design problem and process*. The way in which a design problem is broken down and understood by the design team will frequently affect the product's architecture: one might even say that the structure of the problem will be reflected in the structure of the product. If a given task has X predominant components, or a product is intended to perform X discrete functions, then there is a very good chance that the product's final architecture will have one module dedicated to each of those tasks.

Consider the design of a bicycle. It is possible to break down the problem of designing a bicycle into the specific functions that the bike must perform, and map their relationships to the bike's component parts. In this instance, each function is *primarily* embodied within a single module. The bike is *powered* with the crank set (pedals, crank arm, gears, chain, etc.) that interfaces with one of two modular wheels in order to transfer energy and *enable motion*. Motion without *control* is not very valuable, and so handlebars connected to the steering tube and fork allow the rider to turn the front wheel and direct the bike. Similarly, modular brakes *stop the bike* when actuated by levers mounted to the handlebars. The bike seat supports the rider, and the frame connects all of the other modules, while also supporting the rider and transferring forces.

Figure 5.5: The bicycle is an example of a highly modular architecture that reflects the natural decomposition of the design problem; every module is visible and serves relatively few functions.

At the same time, saying that each function is reflected in a single module is an overly reductive statement. First, it is highly unlikely that *every* function can be neatly isolated within a single module. Supporting the rider, for instance, is not actually accomplished by any single module e.g., the seat. This function is actually distributed over the seat, pedals, and handlebars, which transfer the weight of the rider (and the motive power of the leg muscles) to other parts of the system—the frame, the front and rear hubs, the spokes, and ultimately the wheels. Additionally, the majority of modules will support multiple functions. The wheels permit motion independent of the frame, support the frame, provide traction with the ground, permit repair and replacement, and enable braking, at a minimum. Finally, it is possible to decompose the architecture of a bicycle in increasingly detailed ways. The modular wheel can be further broken down into the tube (holds air), the tube-valve (permits filling), the tire (protects the tube, contacts the ground, and increases friction), the rim (maintains the circular shape, attaches the tire, transmits torque from rear hub to tire, and forms part of the braking mechanism), the spokes (support the rim's shape, transmit torque, and connect the wheel to the hub, which permits the tire to rotate independently from the frame), and the sprocket (interfaces with frame and hub, and converts force from the bike chain to torque).

Nevertheless, the way in which a design problem is naturally decomposed is likely to have bearing on the product's architecture. The bicycle is an excellent example not because it is unique, but because each module is simple and serves a small number of primary functions. The decomposition of the problem is reflected in the bicycle's architecture, with most functions primarily existing within a single module. This pattern is maintained as products scale in

complexity: the structure of the design problem is often reflected in a product's architecture to one degree or another.

Further, as design is a temporal activity, the *order* in which designers identify and tackle problems can influence a product's architecture. The design process is a joint exploration of the product and the problem [55], [64], [215]; modular chunks often emerge and solidify in the order in which they are recognized, as it is impossible to define architectures based upon information and insights that the designer does not yet possess. Accordingly, there is a tendency for features that arise later in the design process (after a product's core architecture is defined) to appear as modular pieces added on to the existing structure. This is most evident in situations where features are added near the end of the design process, often as the result of information acquired through evaluative prototypes and testing.

Figure 5.6: Kodak's waterproof single-use camera began as little more than a plastic shell, and slowly evolved into a more integrated component.

In the initial development of Kodak's one-time-use cameras (the Funsaver line), the 'Weekend' model's plastic shell is an example of a late–arriving design idea that was incorporated as a modular component. Because the development of the camera was a closely held secret, the prototyping and testing process for the Funsaver was performed by Kodak employees taking the prototypes home over the weekend. During a kayaking trip, one employee accidentally dropped the camera in water. Knowing that the film could still be developed so long as it remained wet, he returned the camera in a plastic bag full of water. This led designers to the notion of covering the camera in a clear plastic shell. Rather than waterproofing the camera in any sort of integrated way (rubber seals, new materials, etc.), a modular plastic sheath was added as one of the final

production steps—"…there was no basic redesign needed of either the product or the process" [241].

Had the insight to develop a rugged waterproof camera occurred earlier in the design process, the camera's architecture might have looked quite different. As it arose near the conclusion of the process, however, the shell was included as a highly modular component that necessitated minimal changes to the basic design. With subsequent design iterations, the need to develop a waterproof version of the camera was known from the outset. As a result, the case gradually became more and more integrated over the course of future product generations. With the advent of 'extreme' sports, the waterproof version of the basic camera evolved further into a highly integrated, rugged shock and waterproof version, as seen above.

Organizational structure is another factor that can have a large bearing on a product's architecture. A key aspect of defining a product's architecture deals with delineating boundaries and defining interfaces. Similarly, within the designing firm, tasks and objectives are allocated to smaller organizational units (e.g. teams, divisions, etc.), which define a mapping between teams and their responsibilities within the process. This structure enables the smaller organizational units to focus on specific subsets of the product or problem, as well as a limited set of constraints. Setting up a product development team in this way naturally facilitates the design process by reducing the complexity confronted by any individual team, but the organization's structure is typically reflected in the architecture as a result.

The structure of an organization will frequently bias designers towards certain architectures, just as certain architectures may also exert an influence on the structure of the firm. In the *Soul of a New Machine*, Tracy Kidder portrays the race to create a new computer at Data General Corporation, which was launched in 1980 as the Data General Eclipse MV/8000. Kidder tells the story of a Data General project leader and long-time Digital Equipment Corporation employee who, upon opening a DEC computer and examining its structure, stated that he saw "…Digital's organizational chart in the design of the product" [242].

There is some debate as to which direction this influence flows: does the organizational structure influence the architecture? Or does the architecture exert a greater influence on the organization? A number of authors advance evidence that products themselves actually 'design' organizations, and that organizational structure follows from the architecture of the products

that they design [235]. They contend that modular products give rise to modular organizations, and integrated architectures are most effectively managed by integrated organizations [243]. Others note that the pre-existing organizational structure has a greater impact on product architecture than architecture has on the organization, and that this organizational momentum shapes the way in which modules and interfaces are defined [244], [245]. In all likelihood, both organizational structure and product architecture exert an influence on one another [79]. This mutually influential relationship shifts towards the organization or the architecture depending upon the specific context, product, or organization. It is most likely that architecture and organization change in response to one another—in a co-evolutionary way [246]. Because of the momentum inherent in large organizations and companies, it also seems probable that previously established organizational structures may be difficult to change. Thus, established organizational structures frequently pass this structure onto the artifacts being designed.

This is an intriguing question that illuminates how product architecture can have consequences far beyond the artifact itself. As we have seen with the Boeing 787, the system architecture can have ramifications across the entire supply chain of a complex product, and in fact can define the structure of the supply chain itself. When General Motors spun off its parts divisions into a separate firm, Delphi Automotive Systems, in the 1990's, the question of which divisions to keep 'in house' and which to spin off into the new company were in effect dictated by the system architecture of the automobile.

These organizational aspects of product architecture naturally lead to a consideration of *legacy factors* which predispose designers to particular architectural breakdowns. These factors are also connected to the notion of path dependency, as these are the factors embodied within past products that give rise to future architectures. Legacy factors include previously developed architectures, established standards, shared modules and interfaces, and 'in–house' expertise, and are often some of the largest factors influencing product architectures.

A new version of a product is likely to embody an architecture similar to the *previously developed architectures* which preceded it. This can be seen in generational product variants that are updated and redesigned in order to leverage new technology, improve performance, or provide greater capabilities. A product like Apple's iPhone can be seen as a good example: the original iPhone was followed by the iPhone 3G, which was followed by the 3GS, and so on. Over the lifetime of these products, the iPhone's core product architecture has largely been maintained.

Certainly, new modules have been added, and the structure of the modules themselves have changed in order to provide new functionality or leverage new constraints, e.g., the addition of a front–facing camera module, or the miniaturization of the main board as a result of changing technological constraints.

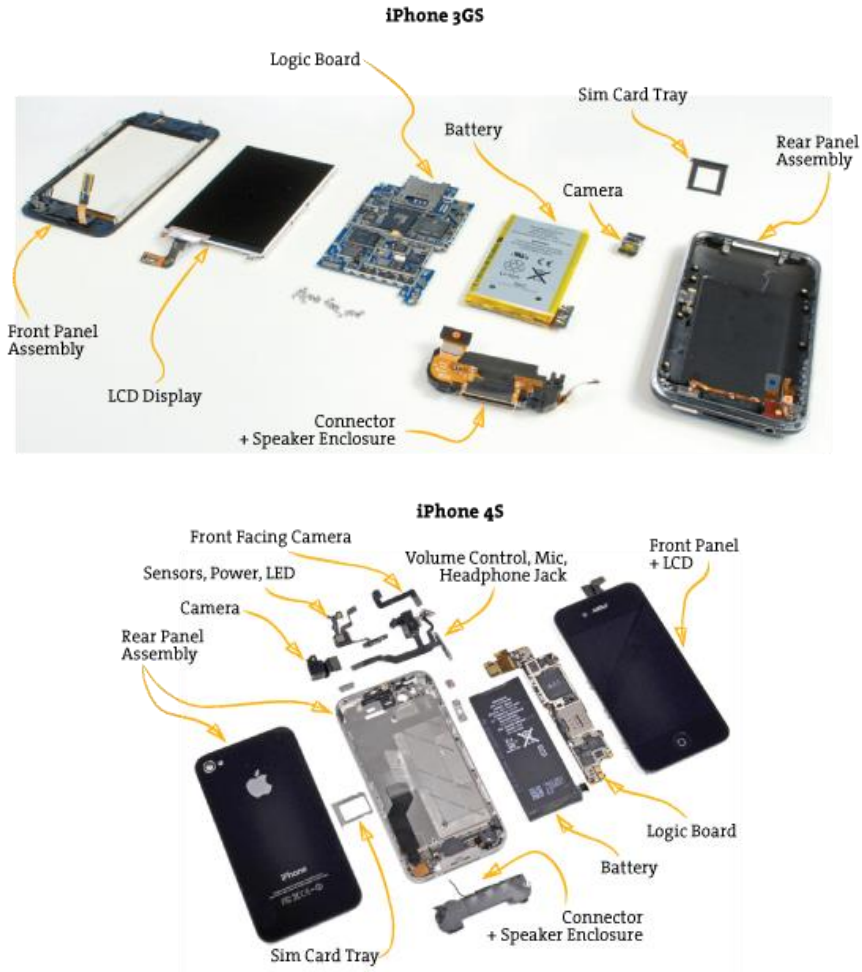


Figure 5.7: The core architecture of the iPhone has persisted across multiple generations—3GS (top) [247] and 4S (bottom) [248].

In instances where all of the products are designed by a single organization, it is likely that the architecture is maintained for multiple reasons. First, the initial architecture has proved successful enough to warrant a new variant product. Secondly, the architecture has almost certainly resulted in established manufacturing processes, assembly processes, team structures,

etc. that would all have to be redesigned should the architecture change radically. Maintaining these architectures allows organizations to leverage embodied costs. Finally, one cannot discount the cognitive reasons the architecture is likely to be maintained: just as innovative ideas are more difficult to generate than derivative ones, so too are totally new architectures.

The pattern of reusing existing architectures frequently holds true across similar products as well. When an organization learns from what has already been done, an established architecture will attain a certain amount of momentum, even across distinct product lines. Returning to Apple, the basic high-level architecture of the iPad looks very similar to the iPhone, whose architecture shares a great deal with its predecessor, the iPod. While these devices address different sets of constraints, and carry different functionality, the structure of the solutions is similar enough that Apple was able to rely on similar architectures. Again, these architectures are not identical, and certain functional elements have been grouped in different ways. The reason that this core architecture is maintained across the iPod, iPad, and iPhone is likely a combination of practical factors (e.g., reduced time–to–market, design process, organizational structure, fabrication capabilities, etc.), cognitive factors, and organizational knowledge.

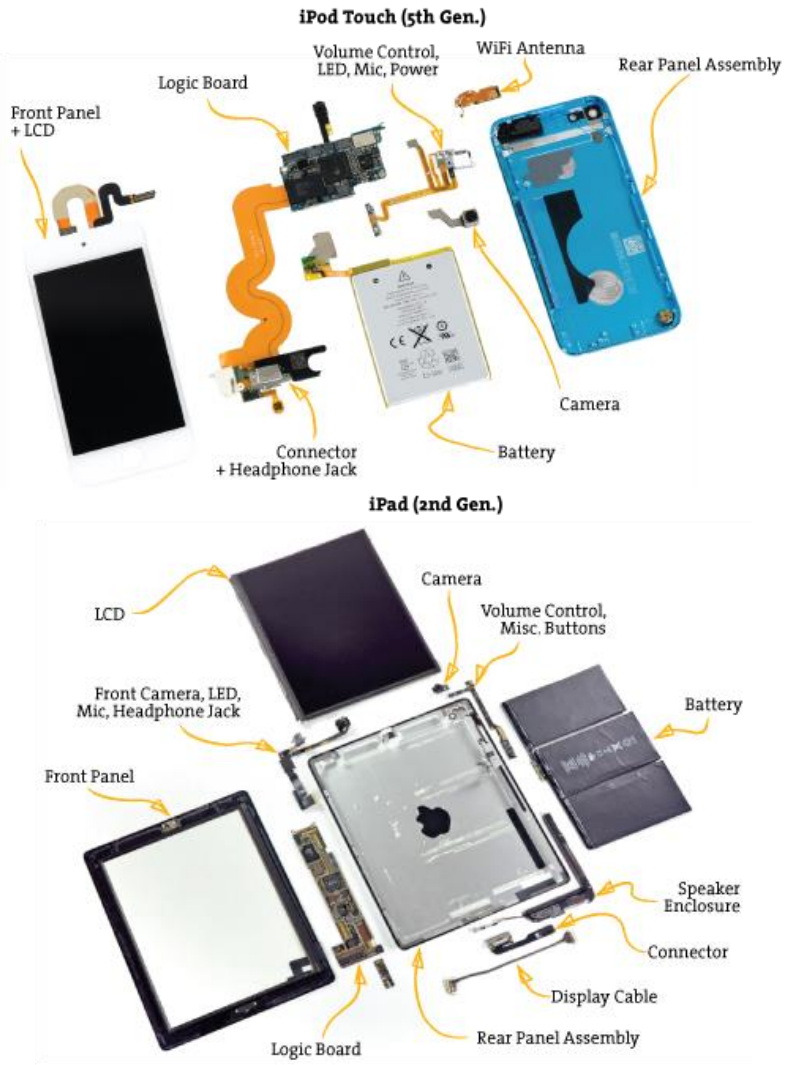


Figure 5.8: The core architecture of the iPhone can be compared to the iPod Nano (left) [249] and the iPad (right) [250].

Even in instances where products are not designed by the same organization, there is considerable evidence that architectures are often quite similar in products within the same market segment. The reasons for this are harder to pin down, but are likely the result of an awareness of competitors' products, best practices, and competitive analysis (e.g. benchmarking and teardowns). It may also be the result of multiple organizations using a similar product or technology as a reference point for a design. Quite often, firms and organizations converge on similar architectures as a result of that architecture's appropriateness for a given problem or constraint context [45]. Consider, for example, the convergence of design across products such

as power hand tools, kitchen appliances, or video game controllers: clearly, certain architectures have been proven effective, and come to dominate market niches.

Another legacy factor is *established standards*. Standards impose constraints on the design of the architecture in order to maintain relationships across products, components, and manufacturers. These factors are (typically) embodied within the artifact system rather than the product itself. Frequently, these standards affect the interfaces and protocols of a product, more so than the product's modular chunks. For example, a desktop computer manufacturer attempting to move away from standard hard drive interfaces (e.g., EIDE and SATA for internal drives, or USB, FireWire, and eSATA for external drives [251]), is likely to be met with resistance from users and hard drive manufacturers alike. In this way, standards exert themselves as market and usage constraints that reinforce existing interfaces. There are, however, standard architectures whose utility helps to maintain a degree of architectural momentum. The modularity of car tires, for instance, is a standard architecture that facilitates the interests of stakeholders throughout the system (repair, replacement, preventative maintenance, etc.), and is unlikely to be changed.

Finally, artifacts that exist as a part of a larger *product family*—a group of similar products or technologies that share physical components, assemblies, manufacturing methods, etc. [252]—are constrained along certain parts of their architecture. This is perhaps easiest to illustrate using product families that share a physical component. Identical batteries, for instance, power the entire DeWalt family of power hand tools. In using this common component, the power source does not need to be designed and integrated within each design, saving time and resources by streamlining the design process. This strategy reduces the complexity of manufacturing and design activities because the battery is designed and manufactured independently of the tools themselves, eliminating the need to design and manufacture additional tooling, and allowing for the re-use of common parts so that costs scale with increased production. Savings generated from the use of this common module can then be passed on to consumers. Aside from reducing costs for the manufacturer, consumers are not required to purchase more than a single battery pack, thus the cost of the battery is amortized over multiple tools. This modular strategy also increases the likelihood that users will purchase other elements of the product family, since they already own the one crucial component.

Figure 5.9: A selection of the many DeWalt tools that can run off a common lithium-ion battery.

DeWalt could redefine the architecture in such a way as to move away from this shared battery in future products, but in doing so, they would forfeit many benefits. Organizational structure, standards, and previously developed architectures establish constraints that provide momentum to particular architectures. These factors do not mean that architectures and interfaces cannot be changed—or will never be changed—but rather, that moving away from these architectures demands significant gains in other parts of the product system to compensate for the loss.

In 2012, Apple introduced the 'Lightning' connector intended to connect devices like iPods, iPads, and iPhones to computers and chargers. When Apple decided to transition from the previous 30-pin connector, they chose the proprietary Lightning interface, rather than the Micro USB that is now the standard in much of the mobile phone industry. The decision was justified based upon aesthetics, improved usability (Lightning is reversible and can be inserted in either orientation), and reported reductions to charging times [253]. Eschewing established interfaces meant that new devices would not be compatible with existing Apple peripherals, or ubiquitous Micro USB cables and devices. Accordingly, Lightning has received considerable negative reaction from users, reviewers, and third party manufacturers alike [254]–[256]. For better or worse, Apple has committed to this new interface.

Figure 5.10: The original Apple 30-pin connector, the new Lightning connector, and Micro USB.

Generally, this example shows that deviating from the interfaces and architectures expected by the market is not without cost, and must be balanced against other constraints throughout the system. Changing architectures can have positive impacts, but the process of moving against these factors that influence product architecture is likely to engender significant trade-offs. The design of a product's architecture is unquestionably constrained by these factors, but designers are doubly limited if they remain unaware of these influences. By making these factors clear, the hope is that design organizations will be better able to consciously consider a product's architecture and its implications.

5.4.2 Product Architecture Defines a Plan

Once solidified in a design, product architecture holds implications for every part of the artifact system, and every part of its lifecycle. From product variety and component standardization, to product maintenance and future design cycles, product architecture is a powerful tool that can be leveraged in order to shape the future. As previously discussed, there is a mutually influential relationship between product architecture and the structure of the organization, but a product's architecture influences the *organization* and the *design process* in additional ways. A product's architecture very often determines the way in which it will be decomposed to facilitate design activity. With a highly modular architecture, modules frequently become the responsibility of a team (a similarly decomposed organizational unit) [141], [257]. Thus the product architecture defines what an organizational unit will be working on, and ultimately the range of skills that the team must possess in order to complete the assigned tasks. The complexity of a module and its associated functionality makes demands on the number of individuals, as well as the skills and backgrounds necessary to understand the function and

perform the design task. For example, a design team for a computer power supply will look much different, in terms of its skill set, than a team designing the motherboard.

Beyond the size and make-up of teams, product architecture also dictates the interactions that must exist between organizational units. Clear and well–defined relationships between chunks lead to clear relationships between organizational units; the information passed between units must reflect that nature of the interactions between the chunks. In this way, a product's architecture also defines the communications that occur between organizational units. Tightly coupled components require closer and more frequent collaboration than those more loosely coupled. In the design of a digital SLR camera for example, the team designing the lens may only need minimal contact with the team designing the body, because there is a single, established interface between the two. On the other hand, the teams responsible for the image sensor and the image processor require far greater communication and contact, as changes to one directly affect the other. Additionally, the timing of this interaction must be appropriate as there are often dependent activities that must proceed in the proper sequence—'team B,' for example, needs some output of 'team A's' process before they can proceed. This is true not only for linearly sequenced activities, but also for contingent (conditional) or interdependent (concurrent) processes [141].

Product architecture also defines a plan for a product's *design and manufacture*. The design of a product and its architecture are, in some ways, tantamount to the design of the factory floor and the assembly activities which fabricate it. A product's architecture often dictates the necessary manufacturing processes, the nature of its assembly, the number of steps, and the order in which they must occur. By their very nature, modular architectures facilitate parallel design and manufacturing, including outsourcing, in that these modules can be developed in different locations and by units with differing skill sets. A camera body, for instance, can be designed and injection molded separately from the detailed electronic manufacture of the image sensor, which can be manufactured separately from the lens (which may require precision grinding). Integrated architectures, on the other hand, frequently require more coordinated design activity and more complex linear manufacturing, but may also require fewer assembly steps. There is not a right or wrong way to specify the architecture to improve manufacturing and assembly; integrated is not best, nor is highly modular. Rather, each architecture will place certain demands on the manufacturing and assembly capabilities of an organization.

The way in which demands shift throughout the system based upon a chosen architecture can be illustrated in the development of the world's first modular skyscrapers [258]. Developed by Chinese company Broad Sustain Building, these modular buildings boast extremely fast construction, reduced cost, and reduced material usage. In 2011, Broad built a 30-story building in just 15 days, at the approximate cost of $1,000 per square meter (compared to $1,400 for typical high-rise construction in China). Additionally, high-rise construction typically creates 5,000 tons of water and produces 3,000 tons of construction waste, while Broad's construction methods produce only 25 tons of waste and use no water (primarily due to the elimination of cement).

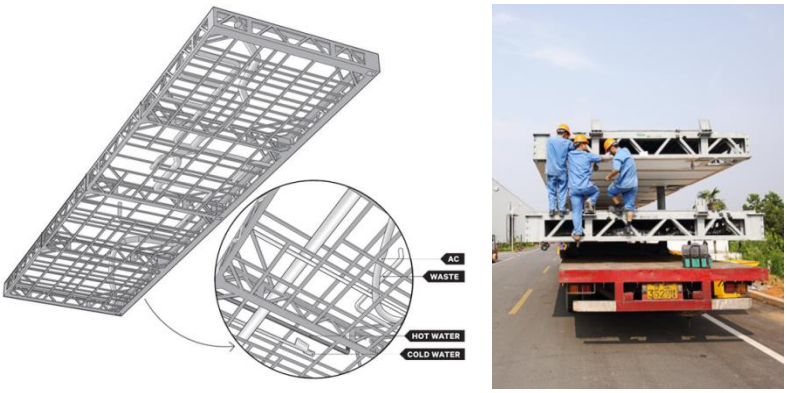


Figure 5.11: Broad's ceiling/floor modules are shipped on highly standardized truckloads [258].

Designing and specifying every aspect of the building's construction before on-site assembly enables these gains. The floors and ceilings of the buildings are built in modular sections, with pre-installed fixtures, pipes, and ducts (that will align once assembled). The customer's choice of flooring is also pre-installed on each floor module. Much like a large-scale piece of IKEA furniture, once fabricated, each modular section is packaged and shipped (in a standardized truckload) with the columns, bolts, tools, and peripherals necessary to begin assembling the skyscraper. Once at the site, each module is assembled by crane using snap in columns, as workers use materials and features already on the modules to secure the structure and quickly connect the pre-installed pipes and wires. Finally, walls and windows are slotted in by crane to finish the on–site assembly.

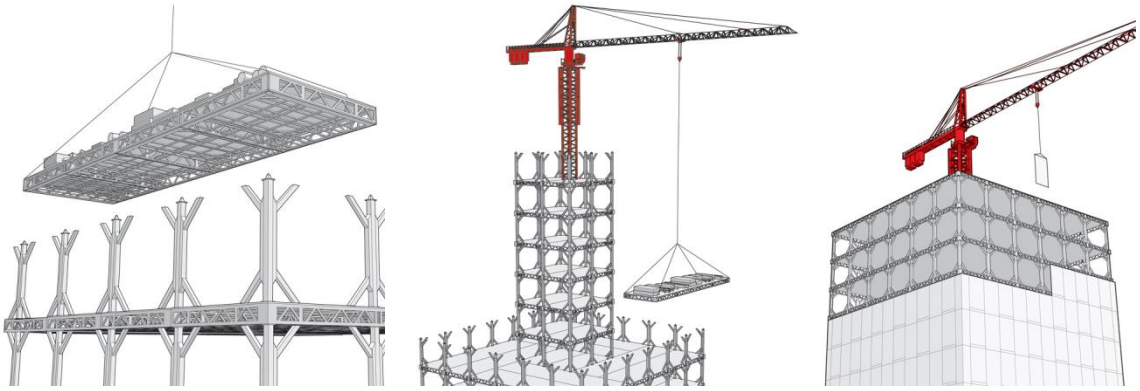


Figure 5.12: Lowering the modular components onto the snap in columns; construction and facing the high-rise from above [258].

These modular skyscrapers represent an innovative architecture with potentially large advantages. Even so, they are not able to escape the trade-offs inherent in complex artifact systems. Modularity greatly increases the ease of assembly, but similarly increases the complexity of the front-end design, manufacturing, factory assembly, and distribution processes. Broad's structures have also been criticized for their dull aesthetics and lack of design flexibility. For example, as a result of the highly standardized pieces from which these buildings are constructed, the addition of a separate pyramid structure was the only way to add a lobby to the T-30 hotel (*Figure 5.13*). Generally speaking, a product's architecture has large implications for how a design will be manufactured and assembled.

Figure 5.13: A picture of modular high-rise construction, and the finished T-30 Hotel in Hunan, China.

Product architecture also has a significant impact on the extent to which products can be *customized*. In general, modular designs along with appropriate interfaces and protocols [90], allow for discrete modules of an artifact to be more easily removed and replaced with alternative modules that carry new functionality, new looks, new technology, etc. From the perspective of the design organization, this customization can be leveraged at different points during a product's life cycle. It can be implemented in the manufacturing facility (to facilitate variation within a product), at the point-of-sale (to differentiate globally available products for local market conditions), or in future products.

In the context of physical products, modularity can facilitate variation within a set of products. In the manufacture of standard cylinder door locks, for instance, each lock must be highly customized in order to serve its functional purpose. High security locks can be produced in batches of up to 1,000,000, each with its own unique key. Rather than having to design 1,000,000 different locks, the architecture of most locks allows for a standard assembly (consisting of a locking bolt, faceplates, mounting features, etc.) to be joined with a unique locking cylinder.

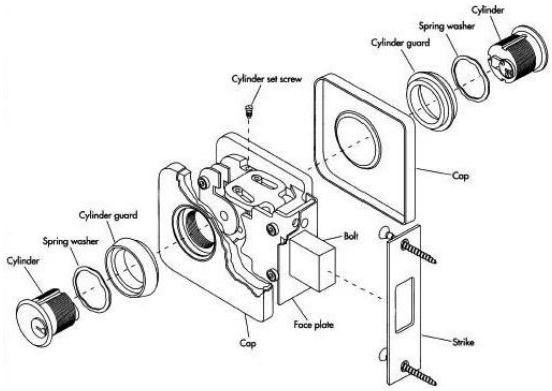


Figure 5.14: The modular locking cylinder on door locks allows for efficient customization.

Taken to the extreme, modularity can facilitate the mass customization of goods, with each product tailored to individual specifications. Mass customization refers to "…the capability to manufacture a relatively high volume of product options for a relatively large market (or collection of niche markets) that demands customization, without tradeoffs in cost, delivery and

quality" [259]. This practice can provide strategic or competitive advantage and economic value [238]. The modularity inherent in the individual tools of a Swiss Army knife, combined with the established interface between the body and the tool, allows a firm such as Victorinox AG to easily produce the knives in a large number of combinations. Simply adding or removing tool modules completely transforms the functionality of the knife. Another example of mass customization is the assembly of Dell PCs, which are built based upon the components and configurations specified by individual customers. In this case, customization is done inside the factory, but the purchaser has specified the combination of components during the online ordering process.

Point of sale customization allows manufacturers to differentiate their products later in the organization's supply network, at a location beyond the initial manufacturing facility. In these instances, co-locating (on one module) the components and functions that need to change from region to region, or market to market, can allow a design to be quickly tailored to a specific context. This offers clear benefits as a single manufacturing facility no longer needs to produce a different version of a design for every region, but can instead produce a single artifact that is differentiated downstream with the addition of a region-specific module. Power supplies for many electronic goods are good examples of point–of–sale differentiation. It is possible to develop different power supplies depending upon the distinct outlets and voltages of a region, but a more elegant solution can be seen in customizable power supplies [6]. Apple laptop power supplies, for example, are built around an auto-switching power supply which monitors the incoming voltage and switches itself accordingly. Coupled with interchangeable adapters that allow the device to be plugged into to a range of outlets, this provides a product with the maximum amount of region-to-region flexibility without placing the burden on an organization's design and manufacturing capabilities. The change of a single module at the point of sale enables a MacBook power supply to function in the U.S.A, Australia, or Korea. Taken as a whole, the customization of a product is often an important aspect of product design that is either hindered or encouraged by an artifact's architecture. Designed in the right way, a product's architecture will allow a design to be brought in line with the constraints and demands of consumers, regions, and markets.

Figure 5.15: Apple power supplies can be easily differentiated based upon standard outlets and voltages.

Architecture also exerts an influence on the design of product families, with certain architectures allowing products to share components, be assembled for mass-customization, and be differentiated at the point of sale [6]. As discussed, product and technology platforms can contribute to the path dependency of architectures; conversely, novel architectures can open up opportunities for new platforms and product families. DeWalt, along with most other power tool manufacturers, have found a great deal of success developing architectures around a shared modular battery. While Black and Decker is no stranger to this particular architecture, in which the battery is the detachable module, questioning it further led to the development of the Black and Decker 'Matrix' tool. The Matrix is a modular system that allows users to attach multiple tools (drill, impact driver, jigsaw, sander, router, etc.) to a single platform containing the motor, controls, and standard-modular battery. In many ways, it can be seen as the logical continuation of power tool modularization.

Figure 5.16: The Black and Decker Matrix system.

The 20-volt Matrix tool is different from most other power tools in that the power source, the motor/handle/switch module, and the actual working tool itself have each been modularized. The user must only purchase a single battery and a single core piece to which they can attach a number of tool modules, each designed with the gearing necessary for its specific task. Achieving this interchangeability placed additional constraints on the design of the interface between the Matrix platform and each of the functional heads. The motor turns a five-sided male joint that attaches to the matching female joint that has a transmission unique for each tool. The drill transmission, for example, consists of a set of two planetary gears that reduce the motor's 24,000 rpm to 800 rpm to deliver the necessary torque for drilling/driving. The oscillating multi-tool attachment, on the other hand, uses two gears to transfer the motor's rotation into an ovoid motion which moves the drive-shaft, allowing users to cut, sand, or grind [260].

In this way, changing a product's architecture can shift constraints and challenges within the design space, leading to altered design and manufacturing activity. Doing so paves the way for potentially innovative directions with respect to product families and platforms. In this instance, Black and Decker seems to have designed an architecture that is balanced with respect to the constraints present on the design: one reviewer described the matrix as, "…an innovative tool for the home owner at a great value… [that is] almost perfect for any homeowner" [261].

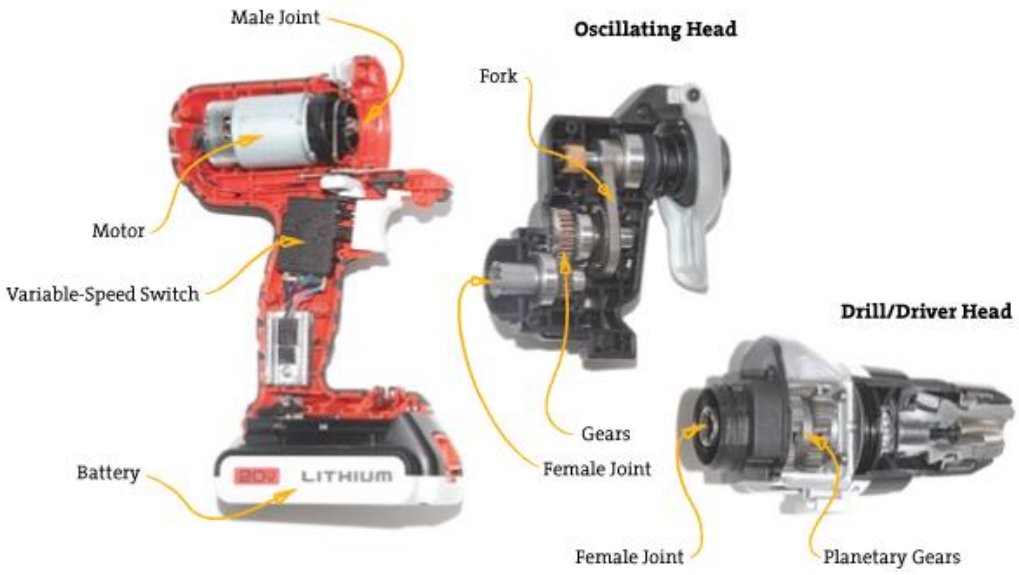


Figure 5.17: The design of the individual heads was complicated by the new modular architecture of the Matrix [260].

Once the architecture of a product is determined, it affects everything that comes afterward. This not only includes details relevant to the product's design and manufacture, but also a number of post-release factors as well. For one, a product's architecture has a large influence on a product's *end of life behavior*, which affects how an artifact fails, as well as how it is maintained, serviced, and recycled. First, architecture defines a plan for how an artifact will fail. Specifically, a failure of, or in, a *modular* chunk does not typically cascade through the system as functional elements are isolated. If a computer's power-supply or hard-drive were to fail, the other modules would not fail as a result. The monitor would still be structurally and functionally sound, as would the keyboard, the mouse, and the graphics processor. This is not to say that the computer would continue to work, as those components are necessary for operation. In order for the computer to continue to function, redundancy of the hard drive and the power-supply would be required. This is not common in PCs, but functional redundancy is something that modularity makes easier, and can be seen in many IT server systems [262].

In highly integrated systems, on the other hand, failures in one component typically lead to cascading failure in others because of the high degree of interdependency. The space shuttle Columbia disaster, which occurred on February 1, 2003, provides an excellent, but tragic, example of the way in which failures tend to cascade within highly integrated systems. The space

shuttle orbiters were highly integrated artifacts in which specific functions were shared across multiple components—a result of the required level of performance per unit mass necessary to lift the orbiter into orbit. On the Columbia's launch, the leading edge of the left wing was damaged by a piece of debris. This leading edge was a highly integrated chunk that had three distinct functions: it served a structural function, an aeronautical function, and a thermal function (to protect the shuttle from the ultra-high temperatures experienced upon re-entry into the earth's atmosphere). When the debris strike occurred, only the thermal function of the wing was compromised; the wing still facilitated flight into the shuttle's re-entry procedure. When the immense heat of re-entry penetrated the thermal barrier, that failure quickly cascaded, resulting in the failure of the wing's other two integrated functions [234], [263].

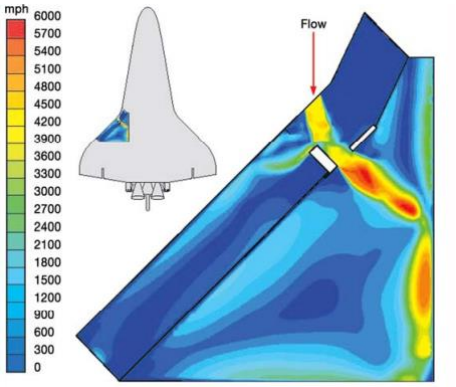


Figure 5.18: The effects of wing Thermal Protection System damage as reported by the Columbia Accident Investigation Board [263].

Had these three functions been isolated across modular chunks this tragedy might well not have occurred as it did. Doing so, however, is simply not an option in the highly constrained context of space travel. Cascading failures can be seen as a general pattern in the failure of highly integrated artifacts. Highly modular designs, in contrast, tend to 'fail better' [262], in that failures are typically limited to one function or one chunk of the artifact. The highly modular International Space Station is more fault tolerant than a space shuttle, in which the failure of a single solar panel or research module is unlikely to have far reaching consequences. The space station, however, can only be modular because it is not forced to confront the difficult constraints related to flight, as each module has been separately shuttled into orbit. Regardless of

context, modular architectures are typically more fault tolerant, and can recover more quickly than highly integrated architectures. Designers must then recognize that like everything else in design, this fault tolerance comes at a price, frequently in the artifact's performance.

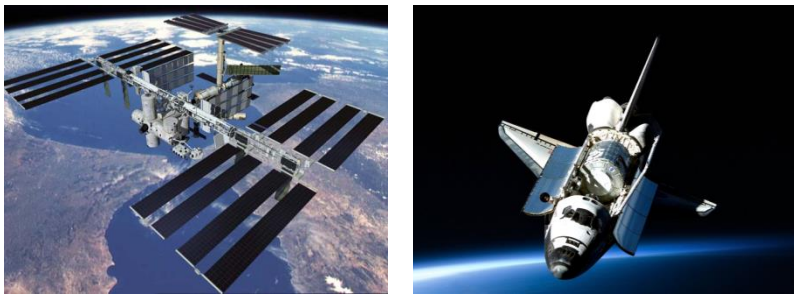


Figure 5.19: Modular architectures tend to 'fail better' than more integrated architectures, but frequently sacrifice performance, feel, or aesthetics.

Once a part of an artifact fails or ceases to function for any reason, repair and service become paramount. In these cases, a modular architecture facilitates easier replacement as a single module can be exchanged in order to restore the product to its previously functional state. This ability to exchange modules expedites and aids in the process of repair as well, by allowing maintenance personnel easier access to the components that make up the modular part. Although a simple example, the modular nature of vehicle tires provides an excellent picture of how modularity significantly eases the process of servicing a product. Should a car experience a 'flat' on the highway, a driver can remove the non-functioning wheel and exchange it with a functioning spare (a redundant component) using only a few simple tools. If the wheel was an integrated component, a flat tire would be a much larger problem.

By properly designing the modularity of the system, it is possible to design architectures that anticipate and support maintenance. One can accomplish this by defining modules that facilitate the removal and replacement of relevant parts, rather than improperly integrating failure-prone parts with durable or more function-critical parts. By designing architectures in this way, it also becomes possible to incorporate modules *intended* to fail to protect more function-critical components. A car bumper, for example, is intended to protect the more integrated and critical vehicle components (frame, drive train, safety systems, etc.), and can be replaced much more effectively than the rest of the vehicle. Printer ink cartridges and disposable batteries are

similar examples of modular chunks that can be replaced when their resource is consumed [6], rather than as a result of damage or failure.

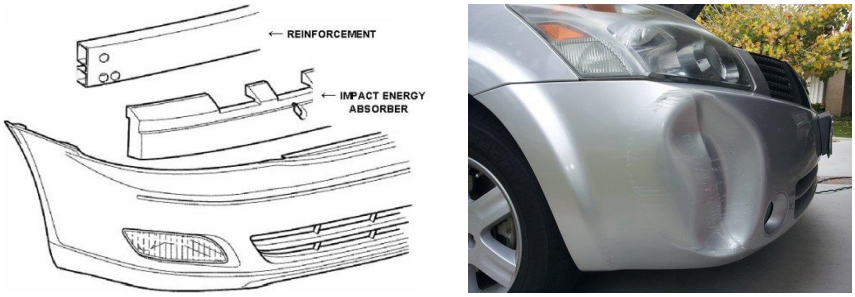


Figure 5.20: Modular bumpers are intended to fail and protect the more integrated systems critical to a cars operation and safety.

Once a product has reached the end of its life, its architecture also has bearing on how it can be disposed of, or reused. Recycling, for instance, is focused on recovering raw material, or slightly degraded material that is still useful. Architectures designed for recycling are less about how functionality is spread across modular chunks, and more about how materials are integrated into a single component. When multiple materials (composites, two-part molds, or insert molds), are integrated in a single part, recycling becomes much more difficult. 'Insert injection molding,' for instance, combines several materials into a single unit by encapsulating a metal or ceramic insert within injected plastic. This process provides performance benefits by leveraging the best properties of multiple materials—strength, wear resistance, tensile strength, conductivity, etc.—but requires the integrated materials to be separated before they can be recycled [264]. Despite the benefits of producing components in this manner, these decisions must be balanced against constraints related to recycling—a process whose importance will continue to increase for the foreseeable future.

Figure 5.21: Insert molded parts can combine the benefits of multiple materials, but can be quite difficult to recycle.

Once in the context of use, a product's architecture has the ability to *facilitate change*. Changing a modular chunk is much easier than changing a chunk with a great deal of functionality integrated within it, which is nevertheless simpler than the worst case scenario, changing a chunk which contains functionality that is spread across multiple chunks. This change is not limited to manufacturers and retailers, and can be extended to consumer users as well. A modular chunk can frequently be changed without affecting the design or functionality of other chunks, thus facilitates factors like upgrading, consumption, and flexibility in use [155]. This provides great value, as it can allow end-users to bring a device's functionality more in line with current needs.

Modular upgrades are also used to expand capabilities, improve performance, or change the appearance of an already existing product. Because of the well-designed modularity of the desktop PC, users can easily replace or upgrade specific modules related to the computer's performance. If a user needs more storage space, the hard drive can be upgraded without complication, just as the performance of the computer's memory (RAM) or processor, can be independently upgraded based upon a consumer's specific needs. This same logic extends to the peripherals as well, with users able to upgrade display and control devices—monitor, mouse, and keyboard—to fit their particular desires. A quick look at the history of the desktop computer shows that the system architecture has shifted from highly integrated to highly modular in order to facilitate just this sort of upgrading and customization.

Figure 5.22: An early integrated PC in contrast to a more modular modern PC.

While upgrading is geared more toward linear enhancements, architecture can also afford adaptability and flexibility in use that provide a product with the ability to perform across a wider range of contexts, allowing the artifact to more effectively cope with variations in tasks, inputs, and user goals. The interchangeable lenses of an SLR camera can be seen as a good example of how product architecture can facilitate adaptability, as lenses can be quickly and easily switched to meet the needs of every shooting situation. There is a vast difference in a camera's capabilities if a 200mm telephoto lens or an 18mm wide-angle lens attached: from a functional perspective, they might as well be different cameras.

Figure 5.23: Changing lenses fundamentally alters the way in which a camera performs for a user [265].

Another excellent example of designed–in adaptability facilitated by a supportive architecture is the KitchenAid stand mixer. The adaptability of the stand mixer manifests itself at two levels. First, the mixer's rotating shaft has a common physical interface which allows users

to attach any number of different beaters—the variety of wire whips, flat beaters, and dough hooks are each designed to serve a particular purpose. Users must simply decide which tool is appropriate for a particular task. Secondly, by connecting new modules to the mixer through the mixer's 'accessory hub socket,' users can further transform their mixer. Each of these modular add-ons enables the KitchenAid to perform an entirely new function. There are attachments that transform the 'mixer' into a food grinder, juicer, pasta roller, grain mill, rotary slicer, ice cream maker, and sausage stuffer just to name a few. In all of these instances, users are changing one modular component rather than switching between different products, each with unique functionality.

Figure 5.24: The KitchenAid stand mixer's two levels of adaptability, facilitated by modular upgrades.

While the ability to accommodate change is critical to the success and performance of many products, architecture is also a key to how organizations can deal with uncertainty and unexpected constraint change. Upgrades, add-ons, maintenance, consumption, and flexibility of use are all closely tied to the designer's ability to anticipate change. While it is possible for designers to predict change to a degree—designers can safely predict that a car's tires will wear out and need replacing before the rest of the car—they cannot anticipate the full range of use, failure, and constraint change. In the face of change, modularity can provide designs with greater agility and the ability to change in step with the constraint space. The ability to evolve physical products through changing modular components is not inherent to all modular systems; rather, considered and intentionally crafted product architectures are required. There is a cost associated with the design of evolvable and adaptable architectures, and that price "…will be paid in careful

design and modest amounts of special hardware to facilitate the basic operations of the system" [231].

5.5 Architecture, Evolution, and the Changing Constraint Space

5.5.1 Stable States

Arguably, the main advantage that modularity affords to a product system is the support it provides to artifact variation. Whether the issue is mass-customization, flexibility in use, or upgrades over time, support for variation is a critical component that facilitates the selection necessary for an adaptable system [176]. While it is well established that modularity facilitates evolution [27], [54], [235]–[236], [262], [266], modularity by itself is not enough to support evolution in product systems. Hierarchy, near-decomposability, protocols, and interfaces must all be appropriately managed to allow for design evolution.

Herbert Simon was one of the first to write about these factors and how they facilitate evolution in his 1962 paper, "The Architecture of Complexity" [27]. He presents his case for structures that facilitate evolution using the now famous parable of the two watchmakers. This parable tells of Hora and Tempus, two expert watchmakers who both made very complex watches constructed of 1,000 parts. In assembling the watches, both watchmakers were subject to phone calls from customers that had to be answered, necessitating they stop their assembly. The only difference between the two watchmakers was that Tempus constructed his watches in such a way that the entire assembly would fall to pieces if he had to put it down to answer the phone (whether that was an assembly of two parts, or 999). Hora, on the other hand, designed his watches so that he could put together sub-assemblies of ten pieces each. These sub-assemblies could then be combined into a completed watch. This difference in product architecture allowed Hora to lose significantly less of his work when he was forced to answer the telephone. Subject to repeated interruptions, Hora could assemble a watch in a fraction of the time of Tempus.

The lesson of this parable is highly applicable to physical artifacts: "…the time required for the evolution of a complex form from simple elements depends critically on the numbers and distribution of potential immediately stable forms" [27]. This lesson is particularly relevant

not just for the design and assembly of a single artifact, but also for the ways in which artifacts can change over time. The hierarchy and modularity of a physical artifact provides design organizations with the ability to generate variation in chunks of the design, rather than having to re-design the entire artifact from the ground up. It also allows different elements of the design to change at different rates, rather than forcing the entire artifact to change at the same speed.

In this way, modular architectures provide *stable states* [27], [28], [266], which are key to a design's ability to change within the design process, in the market, and over multiple product generations. Within the design process itself, modularity allows stable states on which selection can act within the context of the reflexive conversation [55], [64], [169]. Partial results and design concepts that represent noticeable progress toward a goal act as stable states, thus allowing designers to build on ideas while increasing their understanding of problem. Each successive iteration solidifies some aspects of the design, which in turn allows designers to explore even further. As a result, designers are not required to arrive at a complete and fully formed solution to a design problem before they can pursue other directions and possibilities. One stable concept allows for the exploration of the surrounding constraint space. If a better alternative or direction is identified, it can act as a new stable state. If not, designers can return to the previous stable state design and continue to explore. In this way, stable states act as both a safety net, and a jumping off point for further exploration.

A case in point is shown in the *Figure 5.25*. In designing a bicycle brake lever for a user whose fingers do not extend past the first knuckle, ten stable state solutions facilitated the generation and exploration of hundreds of variant concepts [267]. Each stable state design (*Figure 5.25*) represents a concept that was solidified and showed significant potential. Each was sketched and prototyped in order to validate the embodied ideas, and also to explore for new ones. At the same time, the design was not a linear process with ten discrete steps. Instead, these ten stable states facilitated the generation of hundreds of ideas and the exploration of many alternative directions. The earliest brake levers were simply cut out of cardboard, but allowed the designers to understand and evaluate the concept in a way not previously possible [64], [169]. Each stable state concept led to further exploration and ideation, which had to be solidified before it too could be evaluated. As the process continued the fidelity and quality of the prototypes increased [209], but none of this would have been possible if the design, like Tempus's watches, had to be completed in a single pass.

This example is focused on stable states within a single modular chunk, a brake lever. In the design of an entire bicycle, similar explorations (based around stable states) most likely occurred for every component at every level of the artifact hierarchy. Simultaneous design activity, occurring at multiple levels of a design is a characteristic of most design processes, further increases the importance of stable states. If it were not for these intermediate solutions, all of the ideas—for every modular chunk, at every level of the hierarchy—would need to be arrived at in a single pass. Simultaneously balancing constraints at a single level for a single module is much more practical than doing so for the entirety of the design.

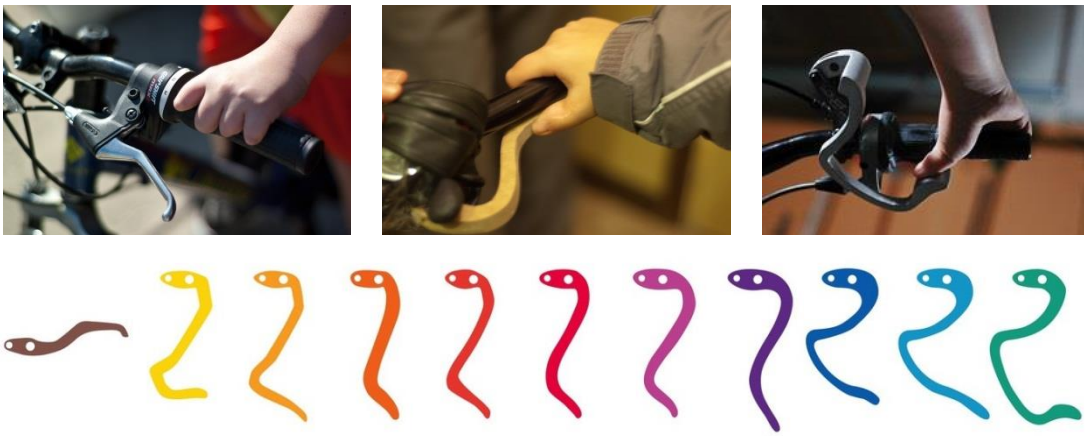


Figure 5.25: The stable state designs in the evolution of a highly specialized bicycle break lever.

Stable states also occur over larger time-scales when dealing with change across multiple artifacts. In this case, the products themselves represent the stable states. Each stable state solidifies a number of ideas and is released into the world, where it can be used as a starting point from which to explore alternative possibilities. This can be seen in the evolution of the iPhone, where each previously released version of the phone acts as an established starting point for the next. These stable states are often afforded and enhanced by the modularity of an artifact as well. With the core of the device acting as a stable state, individual modules can change around it so long as interfaces and protocols are preserved. In this way, variation can occur in modules without necessitating the redesign of the entire artifact. New modules can be designed to change the functionality of the object, and variant modules can be combined in new ways in order to provide new functionality for an artifact's stakeholders.

A clear instance of this type of modularity can be seen in the various types of lenses that can be attached to an SLR camera, each of which change the camera's performance and capabilities. It can also be seen in the ability to attach an adapter ring to the camera's lens mount in order to connect the camera to a microscope for micro-photography. This is an adaptation that clearly would not be possible if the lens was an integral part of the camera. Modularity and standard interfaces allow users to adapt products to their current needs, which may represent a considerable change from the environment for which the artifact was originally designed. In many ways, this allows physical products, otherwise constrained by their physical nature, to evolve and change in response to an always-changing constraint context.

Figure 5.26: A DSLR camera adapted for micro-photography; only possible because of modularity and standard interfaces.

Modularity also affords benefits to designers and organizations in their efforts to stay more in phase with a changing context, even allowing them to potentially kick start evolution within markets. The rapid development of the desktop PC industry can be tied to a change in the product architecture of computers, with the modularity of the computer being one major component "…that has caused the computer industry to evolve to its present form" [232]. When IBM introduced the IBM PC in the early 1980's, the computer's high level of modularity, both in terms of design and production, was a distinct departure from the personal computer market of the day. This modularity lead to the emergence of a large number of companies who would focus their expertise on one part of the system—for example, designing the CPU (Intel), the monitor (Sony) or focusing solely on assembly (Dell). In fact, one can argue that it was the original architecture of the IBM PC that made Michael Dell's innovations possible a decade later.

This change to a more modular architecture can be viewed as the disturbing event which transitioned the PC industry into an *r*-type constraint environment. This emerging industry was characterized by growth, innovation, and opportunity, as well as being highly Darwinian—with no one quite certain which designs or companies would succeed in this highly competitive market [232]. Ultimately, the modularity in the design and production of PCs allowed designers and users to mix and match the best designs from each category of module, pairing the best processor with the best mother-board, with the best hard-drive, and so on. It also allowed designers and users to incorporate new technologies as they became available, rather than having to design every generation of computer 'from the ground up.' This encouraged the evolution of the entire industry, as well as a very high level of innovation in the individual modules, through the increased ability to pursue progress on one component without affecting the design of the other components that made up the PC.

Innovation on a single chunk of the PC also changed the environment in which the rest of the modules existed, and kick started co-evolution in which components took advantage of advances in other modules. The design of a new processor provided chip designers who were focused on memory (RAM) with new challenges and opportunities which could be leveraged in new designs. Advances in RAM chips in turn provided new challenges and opportunities for designers of motherboards, which combined with advances in production technology to allow further advancement of the microprocessor, and so on. These co-adaptive relationships between components and firms ultimately led to the rapid evolution of the PC as a whole. Additionally, the high level of modularity and well-defined interfaces in the PC allowed components to be designed separately (by separate companies). This led to a rapid increase in the number of companies participating in the PC market [237], which then further increased the sources of variation for every component, and the PC market as a whole. The modular architecture of the PC, combined with hierarchy and established interfaces and protocols, provided both designs and designed systems with stable states that afforded increased variation and flexibility.

5.5.2 Differing Rates of Change: Chunks, Layers, and Contexts

Obviously, not all of the constraints within a given product market change at the same rate. As a result, not all of the component chunks within an artifact need to change at the same

rate either. In modern digital SLR cameras, the software that governs the camera changes quickly—with multiple versions of firmware being released for every model of camera. Higher up in the artifact hierarchy, the rate of change of the image sensor is less dynamic than the software, with the camera lenses and the form of the camera body changing more slowly still. Recalling the previous discussion on Brand's layers of change and Holling's adaptive cycle, both are quick to point out that these layers are not completely separate: they frequently exert an influence on one another. While there is clearly 'slippage' between layers, each layer has some ability to initiate or constrain change in the layers around it [46]. The rate of change of the camera lens is quite slow, and as a result Nikon's bayonet lens mount has constrained the change of the camera body. At the same time, the introduction of auto-focus technology led to new capabilities and changes to the camera's internal technology and lenses. Like Holling's adaptive cycles, modularity can both constrain and compel change. Changes in one module led to changes in others, while changes in one module are contained and buffered against by the product's modular nature.

With regard to physical products, there seems to be some corroboration for the idea that the slower a level changes, the more integrated it tends to be. The legacy components of a design—as discussed earlier in this chapter—are far less likely to change, and therefore have a tendency to become more integrated [236]. These components establish some of the trajectory and momentum of many designs and constrain its future course. In becoming more integrated, they become less adaptable and thus more brittle in the face of unexpected events in the future. Recalling the optimality-brittleness trade-off from *Chapter 2*, integrated products can frequently achieve higher levels of performance but are simultaneously more susceptible to change (i.e. more likely to fail).

While core components tend to become more integrated, peripheral components have a tendency to be more modular [236]. These peripheral components—like the buttons, knobs, and dials on a SLR camera—exhibit a smaller (but still potentially substantial) impact on the design. These modular components have the ability to churn and change in order to keep pace with the changing constraint environment, by generating new variation—and exploring new ideas and directions. For example, many buttons have been added to DSLRs in response to the wealth of new features afforded by the onset of the digital workflow, and new buttons are constantly being tried out for their value in giving photographers easy access to certain features. These more

flexible, modular components and chunks are less likely to lead to the artifact's failure, just as they are less likely to lead to a radical reinvention of the product.

Oftentimes, architectures emerge that have given little consideration to these differing rates of change in both the modular chunks and the underlying constraints. These architectures frequently have functional elements that inappropriately span the physical elements of an artifact, thereby hindering the product's ability to change in accordance with the constraint environment. Frequently, this is the result of coupling slowly moving pieces of the design with quickly changing constraints. In these instances, the constraints change too quickly for the component to keep up, inhibiting the larger product's ability to change in pace with the environment. In a DSLR, for example, technological constraints related to the image sensor are some of the fastest moving constraints in the system. These constraints, however, are typically addressed by the most highly integrated piece of the entire camera, the camera body. The camera body integrates some of the most extreme constraints, in terms of their rate of change, into a single component: the constraints on the camera body itself, along with the shutter, mirror, and lens mount all change very slowly, while the constraints on the image sensor, image processor, main board, and digital display all change very rapidly.

Why, then, has Nikon—and almost every other camera manufacturer—chosen to address all of these constraints in the same piece? Would exploring architectures that separate these quickly and slowly moving constraints hold value? As it stands, even if DSLR users wanted to upgrade these components, the highly integrated nature of its design makes that infeasible. At the same time, separating these constraints into two distinct modules—a 'technology' module and a 'camera' module—could open a number of potentially innovative opportunities. Doing so could allow individual users to update the technology of their camera without necessitating the purchase of the full system. This would potentially reduce the cost while increasing the frequency at which users could upgrade their cameras. If this was not a capability that Nikon wanted to extend to individual users—for fear of reduced fit or finish, for instance—designing the camera's architecture in this way could still facilitate more frequent technology refreshing within Nikon's own design cycles. For instance, this architecture could allow Nikon to update quickly changing technology components without redesigning the whole camera.

A valid argument as to why Nikon would not consider doing this is because they actually *want* to sell customers entirely new cameras, at a higher cost. Although this instance is primarily a

strategic business decision for Nikon, there are many other companies that could potentially benefit by providing consumer users with an innovative architecture such as this. In fact, an architecture like this *might* represent a disruptive technology capable of initiating reorganization within the DSLR constraint space. Initiating this destabilization in the market could potentially provide smaller manufacturers with access into a highly competitive *K*-type environment. While this is not intended to imply that this particular architectural change is necessary, it is intended to show the value of exploring novel architectures based upon differing rates of constraint change.

As a thought experiment, suppose that a DSLR manufacturer decided to tightly integrate the camera body and the lens. All other factors held the same, users would no longer be able to exert control in response to changing demands and contexts, because the design would now couple fast changing usage constraints with a highly integrated chunk. This architecture would be inappropriately specified based upon the nature of the constraint environment. More broadly, it follows that architectures in alignment with the underlying nature of constraint change are likely to be more fit than those which are misaligned with respect to how the constraints are actually changing.

A product which inappropriately couples quickly changing functional elements (and constraints) with slowly changing physical components, for instance, is unlikely to perform well over time. This understanding inevitably pushes designers toward consciously 'designing' a product's architecture; providing a similar amount of consideration for how a product should be decomposed to the capabilities it will provide, or how a user will interact with it. The way in which designers establish a product's architecture dictates which components are able to change at rates different than the rest of the system. Just as an artifact's chunks change at different rates, so too does the constraint environment. Some environments change rapidly and are quite unstable (*r*-type), while others change much more slowly (*K*-type). Accordingly, the type of constraint environment (*K*-type versus *r*-type) in which a product is embedded will place unique demands on the design of a product's architecture. In comparison to biology, organisms evolve to meet the demands of their environment, and selection favors organisms fit to that pattern of change. Similarly, product markets and product design processes favor architectures that are fit to the demands of their constraint environments.

Designs released into rapidly changing constraint contexts should logically be more modular, allowing chunks and functions to be altered by either designers or users. This allows

for the artifact to evolve more rapidly, in order to stay more in phase with the current state of the constraint space. Conversely, products released into more stable environments can potentially become more integrated—optimizing performance—with less fear that the environment will shift suddenly. In either case, if the architecture imposed on an artifact is a poor fit to its constraints, it is much more difficult for the design to succeed within that environment (with respect to either competition or speed of change). If a chunk that *should* change rapidly is coupled with chunks that change slowly, it becomes a bottleneck to the entire artifact's ability to adapt. In this way, product architecture has the ability to both advance and retard the artifact's ability to stay in phase with the changing world by encouraging components to evolve independently from one another, and at differing speeds.

5.5.3 Loose-fit, Malleable-fit, and Polycentric Control

In *How Buildings Learn*, Brand asks how architects can begin to design buildings "…so that it does not matter when they are wrong" [46]. This question underscores the notion that designers can never fully understand or predict the constraint environments for which they design. In the context of architecture, Brand states that, "…all buildings are predictions. All predictions are wrong." The design of physical products is no different. Thus it is possible to restate Brand's question: how can designers develop products that maintain fitness as the constraint environment begins to look less like the one originally designed for? In order to avoid highly brittle designs, it is important that designers avoid striving for a perfect fit between their context and the design. Perfect fit is fleeting [46], surprise is inherent, and designers' anticipation is never perfect [68]. The world is constantly changing, perspectives on the constraint space are incomplete, and no design solution is perfect. Even if a design were perfect, it would not be long until the constraints shifted, leaving what was once optimized wholly imperfect.

Designing for a *tight fit* with the current state of the world is the goal of many design processes. This "type" of design strives for solutions which are an exact match to the current state of the constraint space. These designs are closely aligned to a specific set of constraints, and therefore do not typically perform as well as the set of constraints changes. This logic of optimizing for a current set of needs is evident in many user-centered design processes that are focused on meeting a specific set of performance criteria, often at the expense of exploring

future directions [16], [268]. As the constraint environment changes then, these designs are often unprepared to continue to meet the demands of users [63]. While tightly fit designs may perform adequately in slowly changing constraint contexts, their implementation can be particularly problematic in rapidly changing *r*-type environments. Changes to the design context can very quickly lead to breakdowns in the artifact's functionality, or its ability to serve its intended purpose (*Figure 5.27*).

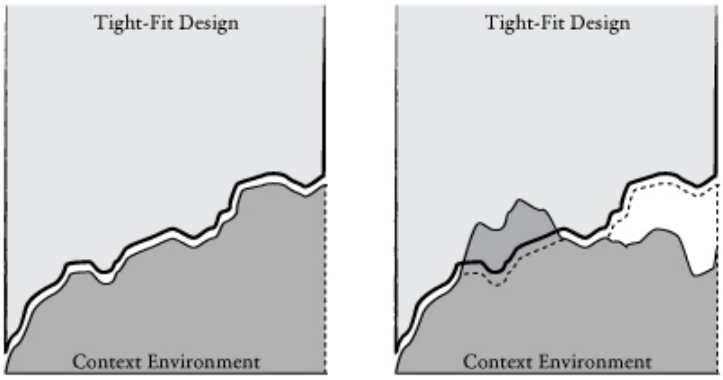


Figure 5.27: Changes to the constraint environment are potentially problematic for tightly fit designs.

Instead, for changing environments, Brand advocates striving for what he calls a *loose fit* with the world by essentially designing buildings which can accommodate change to the constraint environment. In product design, this is equivalent to designing products that have the ability to flex in the face of evolving uses, activities, goals and aspirations (*Figure 5.28*). Doing so can allow a product to handle a wider range of challenges and changing constraints before it is rendered ineffective. As constraints change, a design with a loose fit to its constraint space is able to continue to serve its purpose, develop new purposes, or avoid failure [46]. It is able to continue to function in a world that does not look as anticipated. A loose-fit buffers against designs as hypotheses—since every design will be wrong to some degree—as well as changing environments. It increases the range of possible futures over which the artifact can maintain viability.

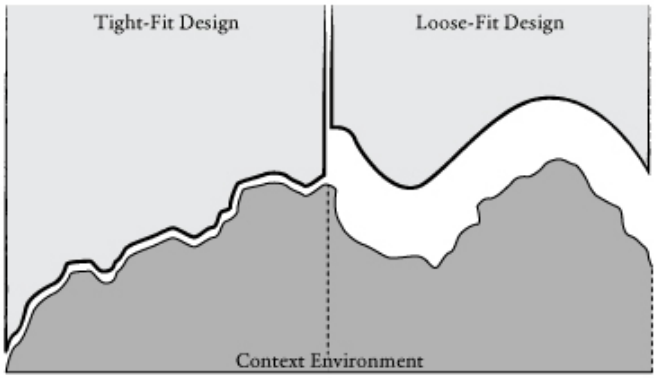


Figure 5.28: A loose fit can accommodate a changing environment, but is less than ideal for the set of constraints.

A flashlight is an example of a physical product that is designed with a loose-fit to its constraint environment. It provides basic functionality (light) that works across a wide range of contexts, and will continue to provide functionality even amidst changing constraints. The flashlight also illustrates a frequent drawback of products designed for loose fit: it is less than ideal for any highly specific context. It is a generalist, and that is its greatest strength. It bends well—accommodating a wide range of uses and contexts—without breaking. At the same time, it is frequently less than ideal for a range of specific tasks. A depiction of this can be seen in the range of highly specific lights available on the market: car headlights, flood lights, snake-lights, and photography strobe-flashes are all examples of lights developed to be more tightly fit to a specific set of constraints. At the same time, these lights are more brittle with respect to any number of unplanned for challenges and constraint sets [90]. A change to one of these specific sets of constraints is much more likely to render the tightly fit light inadequate than the more 'loosely fit' flashlight.

A loose-fit product's greatest advantage is that if its architecture is appropriately designed, it can support the adaptation and evolution of the product with respect to a changing environment. An appropriately designed architecture allows designers to fully specify some chunks of the design—highly finished and fully 'cooked'—but also allows other chunks of the design to be left 'raw'—usable, but not set into stone [46]. The core components and chunks lock in the functionality of the device and change very slowly, but the modular components allow some of the chunks to change frequently in order to adapt to changing constraints. This allows the functionality and capabilities of the design to stay in phase with a changing world.

This is illustrated by the current proliferation of LED technology in the flashlight market. As a result of changing constraints, many flashlight manufacturers have, in a one-to-one manner, replaced incandescent bulb modules with LED modules that offer significantly lower power draw and improved performance. This is an example of modularity being leveraged to bring a design into a tighter fit with a changing set of constraints with respect to the flashlight's design and manufacture. Similarly, this capability can be extended to users as well. Maglite, for example, has brought to market a modular upgrade which allows users to retrofit their incandescent Maglites to achieve the benefits of the newer LED Maglites [269]. The user simply pops out the old incandescent bulb and pops in the new LED module.

Figure 5.29: The Maglite LED upgrade module, as upgraded by the consumer.

A "…key benefit of systems with modular designs is that, especially at the lower levels of the design hierarchy, such systems can evolve" [235]. As a result, systems with architectures appropriate to their constraint space are very tolerant to uncertainty, by providing loose-fit designs with a certain degree of malleability. They are buffered against change in the environment, but over time can be brought into a closer fit with the environment. Through the re-design of existing modules and the introduction of new modules, an existing design can address changing constraints, shift capabilities, and define new directions. With this in mind, designers can strategically design product architectures in such a way as to provide not just room to adjust, but also room to grow—room to explore and evolve.

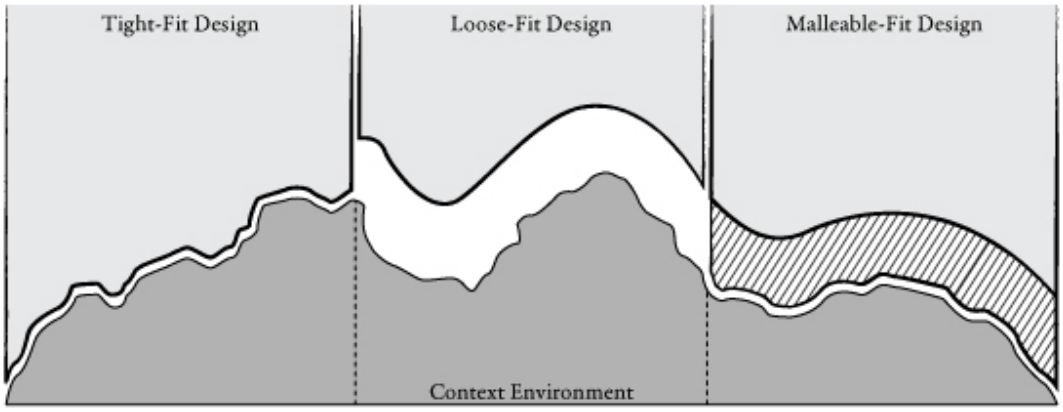


Figure 5.30: Tight fit, loose fit, and malleable fit.

In order to accomplish this, Brand and Mansfield [16], [46] both stress the value of 'future hindsight.' Essentially, the idea is that design organizations should be involved in perpetual re-appraisal and adjustment with respect to the dynamic constraint environment. Both stress monitoring how the world has changed and is changing in response to an artifact, and adjusting anticipation and design activities in response in order to maintain a level of fitness with the environment. Future hindsight places demands on learning from a design by re-appraising the constraints and adjusting in response. Well–devised modularity is key to permitting this sort of activity, as fine-grained feedback and control can only be executed if a design's functionality and structure can be quickly altered—developing new modules rather than re-designing the full artifact.

If designers want to develop a *malleable fit* with the constraint space, treating the constraint environment as an integral part of the process becomes highly critical. Products designed for a malleable fit are not viewed as an end state, but are instead a recognition that products must adjust in response to a changing context. This places an onus on the recognition of emergent information, uses, desires, and constraints in order to adapt to bring the artifact into a tighter fit. In product systems, fine-grained feedback about the state of constraints is not easy to gather, but it is achievable. Fine-grained design response, on the other hand, is seldom possible, as physical artifacts exist as discrete entities. The design, production, distribution, and sale of a physical artifact stipulate that time (often a great deal of time) elapse between the releases of products. Physical products are not continuous, and once new constraints are

recognized, a number of activities must occur prior to the release of another artifact. Manufacturing processes are not evolvable from one object to the next, as tooling, molds, and fixturing take time and financial resources in order to change. Design processes, themselves—responsible for the modules, the artifact, and the manufacturing processes—also take time, as do all of the steps that occur between an artifact's release and its implementation in a field of activity (testing, marketing, sales, distribution, etc.). This discrete nature of physical products exists in stark contrast to the continuously evolving nature of the design's constraint environment [266].

In many ways, trying to design discrete artifacts for a constantly changing world is like trying to answer a continuously changing question. By the time the question is finished being asked, it has changed; and so has the 'correct' answer along with it. And by the time the individual formulates an answer, the question is beginning to look less and less like the one originally asked. This is essentially the environment in which all designers work. Likewise, by the time design research has been translated into a design problem, and that design problem has been solved, manufactured, and sold, the world has changed—trends, goals, desires, and expectations never stop changing. The fact that every answer changes the question only complicates matters even further.

How can designers avoid this problem? How can they develop solutions that are better able to stay in phase with a changing set of constraints? While these are extremely difficult questions, allowing individual users to adapt designs to bring them into a closer fit with their needs is one route that may hold significant promise. Rather than focusing on perpetual re-appraisal and re-design, it may be possible to leverage the adaptability of users. Similar to the discussion of polycentric control, sharp end users have a more current and accurate picture of their own needs and contexts than designers could ever hope for. There is information available at the local level that is not available to designers and designing organizations [12], [69], [84], [217]. Through the considered design of a product's architecture, designers can provide users the ability to leverage their local information, abilities, and creativity in order to exert control over the selection of modules. This also potentially allows for users to adapt modules themselves, in turn altering the functionality and capabilities of the design in order to bring the design into a closer fit with the constraint environment.

While any modular upgrade must be envisioned and facilitated by the design organization, appropriately designed modularity can invite user–initiated change. It is next to impossible for designers to envision every need, every situation of use or misuse, or every desired capability prior to the release of a product. There will frequently be a subset of the user population who are not entirely satisfied with the design 'as is,' and who will set about trying to tailor the product to their specific goals and purposes. Examples of this sort of behavior can be seen in a wide variety of contexts: users have found ways to adapt everything from bicycles and cameras to the Arduino microcontroller and other high-tech scientific equipment [102]. In each case, users with requisite skills and tools alter their artifacts in such a way as to better meet their needs, address specific constraints, or explore new possibilities.

In this way, the malleability of the design does not need to be solely the province of designers. Through appropriate product architectures, designers can extend these abilities to users themselves thus making the system no longer reliant on designers and manufacturers as the sole source of variation and information. Both designers and users can introduce changes intended to meet new and changing constraints. This is not advocating for designers to be removed from the system or a decentralized system of design—a purely crowd-sourced, or user driven model of design. As polycentric control suggests, neither centralized nor decentralized systems will consistently perform. Designers and individual stakeholders all have extremely valuable perspectives on a product system. Many stakeholders (consumer users, manufacturing personnel, service technicians, etc.) are closer to the situation of use, and thus have more accurate and more current information about some aspects of the constraint context. But they are limited by their own bounded rationality, and thus may favor local and acute goals over long-term goals, or the global goals of the entire system. Designers and organizations, on the other hand, have a more accurate perspective with respect to the holistic constraint space, and may be better positioned to envision future possibilities and maintain a long-term planning horizon [38]. If considered architectures can be developed that establish the core functionality of an artifact, but which are simultaneously able to flex and grow in response to the constantly changing constraint environment, designers may be better able to meet needs in a deep and precise way—all while remaining open to change.

These aspects of malleable design are illustrated in the app-enabled smart phones that have come to dominate the mobile market. The hardware components of the phone, in

conjunction with the operating system and pre-installed software, establish the core functionality of the device. But alone these design elements do not represent all of a smart phone's capabilities, nor do they represent a tight fit with the wide-ranging needs and desires of every specific user. These components and features represent the part of the design that is loosely fit to the constraint environment—right out of the box these phones work adequately for a wide range of users in a wide range of contexts.

The countless apps available for these phones, then, comprise the malleable portion of the design as individual users add and remove apps in order to bring the phone into alignment with their current needs and demands. As the world changes and their desires change, so too can the apps—fundamentally changing what their phones can do in the process. In this way, the core functionality of the phone and the hardware are locked in, but rapid change is still supported by the installed software (which itself can be adapted through software updates) and user installed apps (which can drastically alter the phone's capabilities). At the same time, malleable designs do not eliminate the challenges of design. Instead, this view merely poses a new set of challenges for designers, as they now are faced with the task of anticipating and designing appropriate hardware components and features (GPS, front facing camera, etc.) that will enable the creation of compelling apps.

5.6 Moving Toward Designing for Change

The transition to *designing for change* is a necessary but difficult one. It is a leap from the certainties of controllable factors and linear relationships to the complexity of constraint interactions over time. Products are not static objects; rather, they are just one part of a dynamic adaptive system in which products, users, and contexts are constantly co-evolving. Product systems have a life of their own, but by leveraging information from points and perspectives all throughout the system it is possible to construct a picture of the design space that is both more accurate and more current with respect to the actual constraints. At the same time, a considered approach to the design of a product's architecture can lead to products better positioned to change in step with the constraints that define the world. It is clear that the architecture of a product exerts a profound influence on the way in which users interact with a design, as well as the way in which the design will perform over the course of time. Developing architectures aligned with the actual state of constraints is not an easy task; it requires information and understanding about the

structure of the constraint space, as well as anticipation about how the constraints may change in the future.

It is not possible to ever fully predict constraint change; nevertheless, a product's architecture is one of the primary ways to combat this uncertainty. The degree of an artifact's modularity, as well as the way in which that modularity is structured, affect how a product will perform in response to the changes inherent in the actual context of use. The design of a product's architecture is a critical component in the design of the artifact as a whole. Rather than allowing architectures to informally emerge, designers must strive to define architectures that are in alignment with a system's true constraint structure.

Without express consideration given to the product's architecture, it will likely be defined and controlled by local and acute goals, thus limiting the ways in which the artifact can be adapted, and variation generated. Allowing a product's architecture to emerge unchecked can also lead to artifacts that are all too brittle in the face of inevitable constraint change, or not well positioned to address the challenges and opportunities (improvement and innovation) that will arise after its introduction. The importance of product architecture in directing evolution, generating variation, empowering adaptive behavior, and managing designs in unpredictable environments cannot be overstated. If designed effectively, a product's architecture can make it simultaneously tolerant to uncertainty and open to experimentation and change.

Briefly returning to the example of the DSLR camera can help to illustrate how architectures, appropriate to a constraint space, can allow design organizations to better manage complexity and change. The modular nature of SLR lenses, in particular, has proved to be a highly successful architecture with respect to both photographers and design organizations. As previously discussed the interchangeable nature of SLR camera lenses allows individual users to adapt their camera to meet very specific usage constraints, based upon their very current contexts and desires. Each new lens fundamentally changes the functionality of the camera: without moving a photographer can capture a sweeping landscape (wide angle) or an extremely detailed image of a single element (telephoto) just by changing the lens. This well-defined modularity also allows photographers to meet their changing needs in a monetarily efficient way, as a new camera does not need to be purchased for each type of shot. Additionally, because of the standard interfaces, these expensive lenses can be transitioned from camera to camera, as photographers upgrade in order to achieve greater performance or newer technologies. In these

ways, the lens, as a modular chunk, is fit to the constraints and purposes relevant to camera users in ways that a more integral architecture would not be.

The modular nature of the camera lens affords advantages to the design organization as well. Suppose that in the very near future a new lens technology, or a new user demand, will emerge thus altering the constraint space. A camera designed with a modular lens allows the design organization to design and produce a new lens intended to meet these new constraints, without requiring the same investment necessary to design an entirely new camera if the lens and body were integrated. Contrasting these two extremes, the camera with a modular lens is clearly better positioned than a more integral camera. The modular lens camera can more appropriately deal with change (in design, use, fabrication, etc.), as it is better aligned with the constraint space. This logic can be scaled to every aspect of a product's architecture. Specifically, a product with an architecture fit to the underlying nature and structure of the constraint environment will be better positioned to deal with complexity and change.

Designing for change within complex constraint environments is fundamentally about developing the ability to anticipate and recognize emerging constraints, and developing designs and architectures that are positioned to be agile and adaptable in the face of those changes (both foreseen and unforeseen). Doing so requires specific consideration of the type of constraint environment (*r* versus *K*-type), the likelihood of constraint change, and a highly considered product architecture. It should be noted that this is not an argument for modularity *per se*, nor integration. Rather, it is an argument for product architectures that are appropriately matched to their constraint environment at every level of the design hierarchy. Along with all of the other constraints on a design, product architecture is just one more element that must be successfully balanced within the design process.

Physical artifacts, and the constraint environments for which they are designed, are intricately intertwined. Over time, the evolution of the constraint space inevitably leads to challenges and opportunities that can either lead to failure or pave the way for future innovations. Success in these highly dynamic environments, then, is reserved for those organizations most skilled at recognizing the need to adapt, and maintaining the ability to identify and initiate appropriate design changes within a highly interconnected design process fraught with constraints and trade-offs.

Chapter 6: Concurrent Constraint Management Tool

6.1 Introduction

The focus of this chapter is on the design, creation, and implementation of a concurrent constraint management tool (CCMT). The chapter begins with an exploration of some of the existing tools and methods that have been, and are currently being used, to manage the complexity that underlies designed systems. Based upon this grounding the concurrent constraint management tool is introduced and described in detail. The tool was developed in response to the factors and patterns inherent within artifact systems that emerge when they are viewed as complex systems. These factors are often intractable and difficult to manage, but this tool seeks to make more transparent the relevant parts, interactions, and mechanisms that drive their behavior and performance. Accordingly, the primary motivation for this project was to develop a design tool that makes the complexity of designed artifact systems more accessible, in order to help designers to create better designs.

The nature of complex artifact systems gives rise to a number of factors which are difficult to account for, but are critical to the performance of the entire system. Thus the development of this tool was driven by the identification of many of these factors: hierarchy, perspective, interactions, trade-offs, and change. In order to produce a tool that is useful within actual design practice, these principles needed to be made more accessible to design students and working designers. Additionally, designers need convenient ways with which to explore and leverage data that is in alignment with the complex systems they are designing for. Constraints in particular provide a valuable access point, as they allow the principles of complex systems to be tracked and discussed with respect to a holistic set of factors.

6.2 Exploration of Existing Tools

While the concurrent constraint management tool is a novel approach to managing the information and factors related to complex design processes, it is built upon a foundation

previously established by currently existing tools and methods. Accordingly, the CCMT shares a number of features, strategies, and goals with these tools. These tools will be discussed with regard to their application and how they attempt to manage the challenges and complexity of the design process. The two tools that have the most in common with the CCMT are the 'House of Quality' analysis chart and the 'Design Structure Matrix.' Christopher Alexander's design method will also be discussed as it holds many conceptual similarities to the CCMT.

Both theoretically and practically, these tools represent some of the most widely used, accessible, and effective methods for managing the complexity and interactions of design spaces and the design process. As a result of their similar aims, and the shared structure of complex systems, there are clear commonalities between these methods—most notably in their focus on the interactions that exist within the system. As the CCMT shares the intent of making the complexity of artifact systems more accessible, its creation draws upon aspects of each of these tools, but also diverges from them in many important ways. After the concurrent constraint management tool is introduced in *Section 6.4*, the similarities and differences (the ways in which the CCMT diverges from and extends these tools) will be discussed in greater detail.

6.2.1 House of Quality

The House of Quality is a proven and widely used matrix-based tool intended to define the relationships that exist between customer desires and the capabilities of a product or firm. The House of Quality (HOQ) concept was popularized by John R. Hauser and Don Clausing when their article, of the same name, was published in the *Harvard Business Review* [277]. The HOQ is the most basic and most widely used tool of the management approach known as Quality Function Deployment (QFD). QFD, according to its originator, Yoji Akao, is a, "…method to transform user demands into design quality, to deploy the functions forming quality, and to deploy methods for achieving the design quality into subsystems and component parts, and ultimately to specific elements of the manufacturing process" [279].

The HOQ is a matrix-based tool that acts as a "…kind of conceptual map that provides the means for interfunctional planning and communications." It is, according to Hauser and Clausing [277]:

> A set of planning and communication routines… [that] focuses and coordinates skills within an organization, first to design, then to manufacture and market goods that customers want to purchase and will continue to purchase. The foundation of the house of quality is the belief that products should be designed to reflect customers' desires and tastes—so marketing people, design engineers, and manufacturing staff must work closely together from the time a product is first conceived.

This focus on the multiple perspectives that exist within the design organization is one of the great benefits of the HOQ tool when used correctly, and is something that is maintained in the development of the CCMT.

At its core, the HOQ relates *what* the customer wants to *how* a firm is going to deliver those wants, within the context of a planning matrix. It translates market research and benchmark data into a number of quantifiable engineering targets which can be met by the product design process. Its name was conferred because of the matrix's likeness to an actual house once the primary components are assembled. Since its introduction, the House of Quality has undergone many changes and proliferated into a number of different forms, but the basic structure is almost always composed of the same elements: customer attributes, engineering characteristics, a relationship matrix, a correlation matrix, a benchmarking matrix, and an objective measure matrix. Weights, and or relative importance, for a number of the criteria are also frequently included in many HOQs.

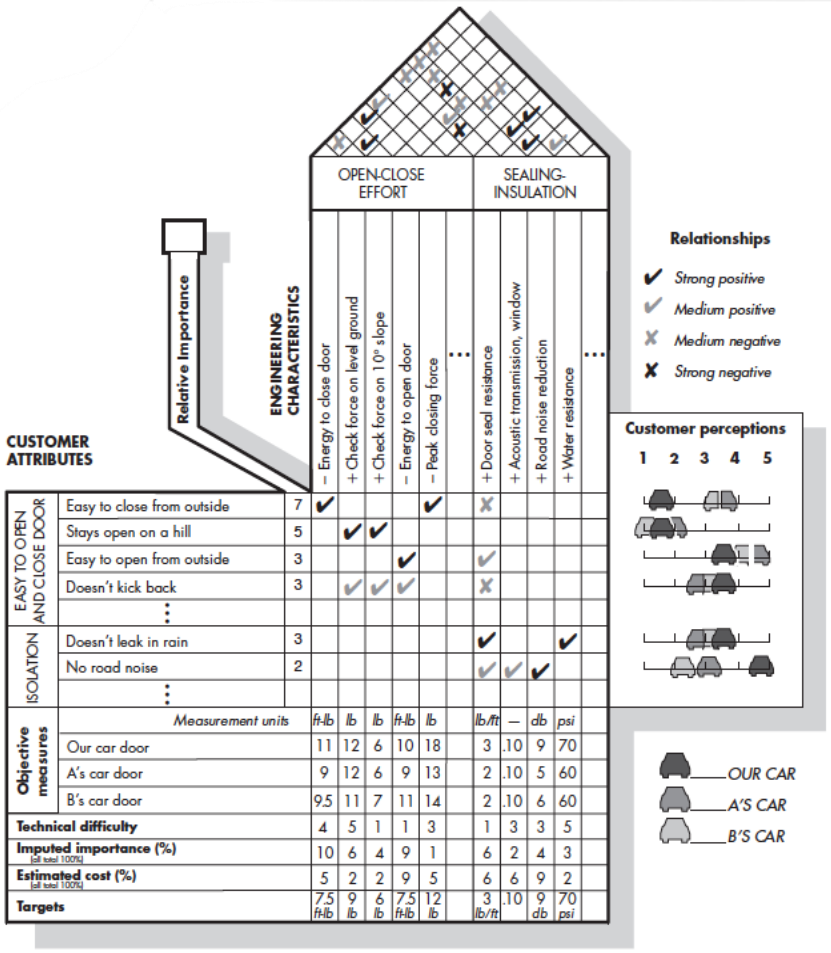


Figure 6.1: A populated House of Quality matrix [277].

The *customer attributes* represent the 'voice of the customer.' They are the specifications, features, and user needs which will be met by the design. These attributes can be based upon market studies, competitive products, or design research; listing these attributes, in many ways, specifies what the design will be and what it will do for the consumer. According to Tapke et al, "…this seems like a relatively simple notion, however, unless customers and producers are perfectly in tune with one another, it may be very difficult to anticipate these features, or each underlying benefit from each producer. It is of utter importance to translate the wishes of each and every customer into some tangible values that can be turned into engineering specifications" [280].

If the customer attributes are the 'what' the product will do, the *engineering characteristics* are 'how' will be accomplished. These are typically quantifiable engineering requirements that can guide the product's creation. These are what the engineering designers focus on in order to achieve the previously enumerated set of customer attributes. The intersection of these two sets forms the *relationship matrix*. This matrix is used to annotate the relationships that exist between the consumer attributes and the engineering characteristics, by highlighting which aspects of the artifact's design are relevant to the customer desires and features. These are typically assigned qualitative measures in order to indicate the nature of the relationship—for example, strong positive, medium positive, medium negative, strong negative—as accurate quantitative data is difficult, if not impossible, to gather for these types of relationships [277].

Each of the attributes and characteristics can be augmented to include a weight or *measure of relative importance*. For the relative importance of the customer attributes the weights are included in a 'chimney' column that exists to the left of the relationship matrix. For the engineering characteristics, it is typically included at the bottom of the HOQ, and can be coupled with other weighted measures such as the percentage of cost, or the relative difficulty of achieving the specific engineering characteristic. These measures can, in some instances, be statistically derived. More often, they represent an informed consensus opinion of the design team or designing organization.

The *correlation matrix* forms the 'roof' of the house, and shows the relationships that exist between any two engineering characteristics. It is intended to capture how changes to one characteristic might affect the others. In certain instances there will be a positive influence, with a change to 'x' benefitting 'y'. In other instances there will be more of what we have referred to as a trade-off, with positive changes to 'x' negatively affecting 'z'. These relationships are once again typically represented using a set of qualitative symbols, as relevant data that accurately depicts the realities of these relationships can be difficult to gather.

The other parts of the House are made up of the benchmarking matrix and the objective measure matrix. The *benchmarking matrix*, is included to the right of the HOQ, and is used to gauge how well a design team has met the customer attributes in comparison to its competitors. Typically rated on a one to five scale, these assessments can be combined in conjunction with their weights in order to provide an overall performance metric [280]. The *objective measure matrix* is included below the rest of the House, and allows the design team to assign objective and

quantifiable data to the engineering characteristics for both their product and their competitors. This can help the team to further assess their position in comparison to the market and to set targets for each of the engineering characteristics.

6.2.2 Design Structure Matrix

While less widely employed than the House of Quality, Design Structure Matrices are another tool intended to map relationships that exist in the design of physical products. Also known as a dependency structure matrix, problem solving matrix, or design precedence matrix, a DSM is "…a simple tool to perform both the analysis and the management of complex systems. It enables the user to model, visualize, and analyze the dependencies among the entities of any system and derive suggestions for the improvement or synthesis of a system" [281]. Eppinger and Browning describe the DSM and its structure accordingly [271]:

> The DSM is a network modeling tool used to represent the elements comprising a system and their interactions, thereby highlighting the system's architecture. DSM is particularly well suited to applications in the development of complex engineered systems…. The DSM is represented as a square *N x N* matrix, mapping the interactions among the set of *N* system elements…. When one is first introduced to the DSM, many find it easy to think of the cells along the diagonal of the matrix as representing the system elements… It is also easy to think of each diagonal cell as potentially having inputs entering from its left and right sides and outputs leaving from above and below. The sources and destinations of these input and output interactions are identified by marks in the off diagonal cells…. Examining any row in the matrix reveals all of the inputs to the element in that row (which are outputs of other elements).

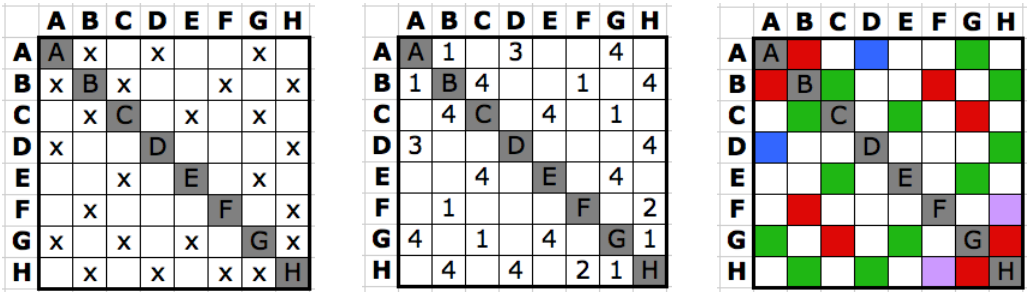


Figure 6.2: DSMs are NxN matrices that can be populated with binary marks, numbers, or colors.

Once built, "…the system is analyzed and structured by rearranging the DSM, either by clustering or sequencing" using specialized algorithms and software tools [141]. And the term DSM is used to refer to both a specific representation of dependencies and the algorithms that are responsible for the reorganization of the matrix [282].

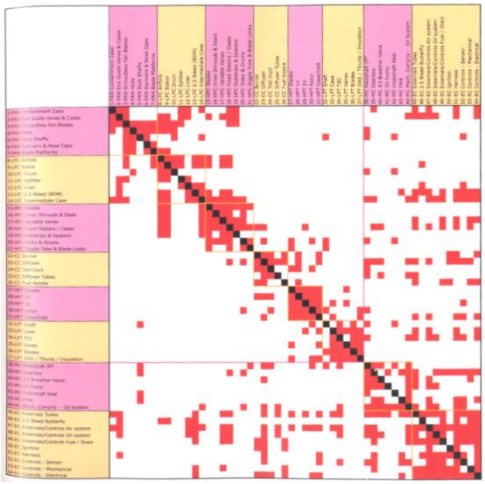


Figure 6.3: A DSM matrix for a Pratt and Whitney Jet Engine [271].

There are two primary categories of DSMs: static and time-based. Static DSMs frequently focus on assessing the relationships between system elements, such as organizational groups or components of a product's architecture. Time-based DSMs focus on a flow over time—the steps in a production or design process, for example. In both instances, the focus is solely on the interactions and relationships between elements within an object or an organization. DSMs have proven useful for a wide variety of disciplines including product development, project planning, project management, system engineering, healthcare management, and organizational design [283]. Within the static category, product–based DSM, the tool has been deployed for a wide variety of research and industrial artifacts ranging from Pratt & Whitney jet engines [284] and the Mars Pathfinder spacecraft (NASA) [285] to the Kodak single-use camera and the Mozilla web browser [271].

While DSMs have been used for modeling organizational structures and activity networks [141], this section focuses primarily on component-based or *architecture DSMs* as they are the most relevant to the design of physical artifacts. The role of DSMs, as they are currently

applied in the product design process, is to identify product architectures appropriate for a given set of components. This can, in turn, aid in the search for innovative product architectures which can lead to competitive advantages for product development organizations [257]. This is achieved through the construction of a representative DSM, which highlights the relationships between the components that make up a physical artifact. Once a component-based DSM is populated—by quantifying the interactions—integration analysis can provide insights into the system decomposition and integration by reordering the rows and columns within the matrix.

Ultimately, these algorithms suggest appropriate product architectures based upon the relationships amongst an existing set of components. According to Browning, "…the foremost objective is to maximize interactions between elements within clusters (chunks) while minimizing interactions between clusters" [141]. Recalling the discussion of near-decomposability, these algorithms are essentially searching for the best way to break an artifact into nearly-decomposable chunks, while minimizing the interactions between those chunks. In effect, a DSM suggests one possible breakdown for the development of a modular artifact.

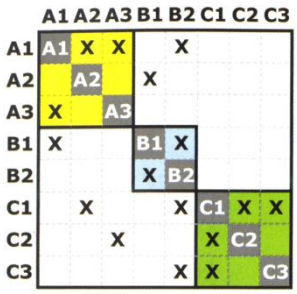


Figure 6.4: A simplified example of a clustered DSM matrix, with three suggested chunks/modules [271].

However, it is "…not yet possible to optimize all of these objectives" [141]. This is not surprising given the nature of complex systems. To get the most out of these component-based DSMs, visual inspection and manipulation are often required [271]. Even when only considering the artifact itself, DSMs cannot ensure optimal architectures and structures, and much of their value comes from suggesting "…alternative architectural perspectives…" [141].

6.2.3 Alexander's Rational Design Method

Finally, attention should be paid to Christopher Alexander's rational design method, which he introduced in his 1964 book *Notes on the Synthesis of Form.* This design method is in many ways similar to a DSM, but expands beyond components to include functional constraints. Alexander's method is a semiformal algorithmic method that determines an appropriate partitioning of a designed system under various assumptions. While focused on architectural design, Alexander's methods have influenced designers from a great number of fields and have bearing on everything from artifact systems to software design [286].

Alexander's rational design method begins by identifying a set of factors (constraints), which may potentially be misfit to the surrounding context. Defined loosely, these factors represent the relevant aspects of a design about which meaningful decisions can be made. They are grouped into a mathematical set, which he calls *M that* is indicative of the aspects of the design that define the artifact's relation to its surrounding context. Alexander insists that this set encapsulate everything relevant to the design. Alexander states [4]:

> The great power and beauty of the set, as an analytical tool for design problems, is that its elements can be as various as they need be, and do not have to be restricted only to requirements which can be expressed in quantifiable form. Thus in the design of a house, the set *M* may contain the need for individual solitude, the need for rapid construction, the need for family comfort, the need for easy maintenance, as well as such quantifiable requirements as the need for low capital cost and efficiency of operation. Indeed, *M* may contain any requirement at all.

It is this focus on a wider range of factors that allows Alexander's method to encapsulate the realities of a design's performance in a field of activity. Once the set *M* is defined, it is possible to define a second set *L,* which defines the links that join the elements within *M.* While Alexander uses the two sets to define a "…linear graph or topological 1-complex…" *G(M,L)*—which he represents graphically (seen below in *Figure 6.24*), this method captures information that is similar to that captured by a DSM.

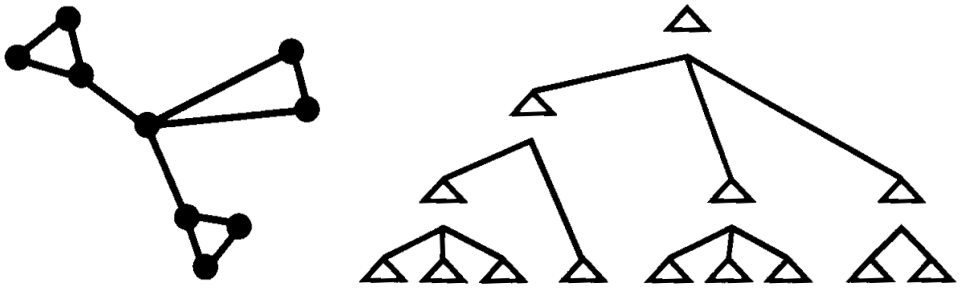


Figure 6.5: Alexander's representation of G gives rise to a more formal decomposition [4].

Despite these similarities to DSM, Alexander's method is, at its core, about leveraging the method in order to identify a *correct* decomposition of the system. It is centered on establishing a particular way in which a designer *should* view a design problem. He states:

> It is very possible, and even likely, that the way a designer initially sees the problem already hinges on a conceptual hierarchy not too much unlike a decomposition in general outline. In trying to show that the links of *L* favor a particular decomposition, I shall really be trying to show that for every problem there is one decomposition which is especially proper to it, and that this is usually different from the one in the designer's head. For this reason we shall refer to this special decomposition as the *program* for the problem represented by *G(M,L)*. We call it a program because it provides directions or instructions to the designer, as to which subset of *M* are its significant "pieces," and so which major aspects of the problem he should apply himself to. This program is a reorganization of the way the designer thinks about the problem.

Just as a component-based DSM suggests an appropriate architecture based upon minimizing interactions across chunks, so too does Alexander's method arrive at a nearly-decomposable view of the problem. He characterizes this output as a specific hierarchical breakdown of a design problem, saying that the "…program really gives us a series of simpler sub–problems, and tells us in what order to solve them" [4]. Alexander argues that in order to best match its context, a solution must be constructed along these internal decompositions, and that the form of the solution is suggested by the structure of the problem as defined by the program. Following this rational design method, then, "…generates design products that are optimally adapted to the microstructure of local conditions and constraints" [286].

Alexander's work is often highly theoretical, but his ideas embody a number of important principles for designing within the context of complex artifact systems. While the ideas are not always the most accessible, their quality and originality is the reason that *Notes on the Synthesis of Form* is still Alexander's most essential and widely cited work. Many aspects of this dissertation and the CCMT have been inspired by these ideas. While the CCMT diverges from Alexander's rational design method, it would look quite different were it not for its inspiration.

6.3 Six Goals for the Development of a Constraint Tool

Based upon the exploration of existing tools and methods, a number of key goals were identified. These goals were developed with the intention of framing and directing the design of a new tool. Accordingly, they encompass the strengths of the previous tools, as well as their weaknesses. In doing so, the hope is that this new tool will be able to carry forward some of what these tools do well, but also build upon their deficiencies and extend their functionality. Six goals were identified as being critical to the management of design activities within complex artifact systems:

(i) reflect the complexity of artifact systems;

(ii) explore alternate perspectives;

(iii) bring clarity to tightly coupled artifact systems;

(iv) support the understanding of change;

(v) encourage collaboration across teams and perspectives;

(vi) be useful and relevant within actual design activities.

While the first five goals all relate to complex systems themselves, the final goal is more related to the tool's application. A great number of design tools and methods have proven pedagogically valuable, without actually impacting real-world design processes. But as design is primarily about the creation of actual artifacts, every aspect of the constraint management tool was evaluated in light of the goal of developing a tool that would have real value both for design educators and for practitioners doing real-world design. These six goals were outlined prior to the tool's creation, and in many ways drove the design process throughout its development. While they have changed slightly in response to emerging uses and evolving aspirations, the set

has persisted largely unchanged. Because these goals have, in some way, all been achieved in the design of the constraint tool, they can be seen as a justification for the value of the tool as well.

6.3.1 Reflect the Complexity of Artifact Systems

Both the design process and a design's behavior in its context of application are messy and inherently unpredictable. Accordingly, it is critical that the constraint tool reflect the complex nature of these processes. In a situation such as this, over-simplification is potentially dangerous. At the same time, some degree of simplification is necessary in order to frame the problem in a way that will be manageable for designers and organizations. The tool must balance simplicity with depth of analysis—helping designers to understand the operation of the total artifact system in a deep way, without obscuring the details and specific interactions that are necessary in order to gain meaningful insights. George E.P. Box famously stated that, "…essentially, all models are wrong, but some are useful…" [270]. Accordingly, the simplifications necessary to develop this tool ensure that it will be "wrong" with respect to the actual system. In order to be useful, the tool must accurately preserve the aspects of the system that define its performance. In short:

- the constraint tool should not "over-model" the system, attempting to specify and forecast interactions, system performance, or design solutions in a highly accurate way. It is a *descriptive* tool, intended for use in conjunction with other methods and tools.
- the tool should not be a prescriptive design method—attempting to replace design activity. It is a representation intended for use in *conjunction* with the other tools, methods, domain knowledge, and creative intuition currently employed by designers. It should aid understanding and exploration, rather than generate solutions.
- the constraint tool should be considered primarily as a way to help designers more fully explore the constraint space for a particular design situation. It should help designers to identify and understand the relevant constraints and relationships across all five constraint categories, at a variety of scales.

6.3.2 Explore Alternative Perspectives

The only way in which it is possible to reflect the complexity of artifact systems, while simultaneously providing insight, is if the constraint tool encourages designers to explore the system from a variety of viewpoints—one perspective is never enough. Complex artifact systems are both hierarchical and nearly-decomposable. Therefore, the constraint tool should encourage designers to explore various viewpoints within that structure: shifting the scale at which they view the artifact system, as well as the constraints on which they focus.

- The constraint tool should help designers to recognize, and shift between, multiple perspectives within the larger constraint set. This includes shifting focus between multiple stakeholders and contexts—viewing the constraints that arise as the result of manufacturing, end-users, maintenance, etc. It also includes exploring perspectives within the design team, and shifting the designers' constraint focus.
- The goal of this tool is not to prioritize a single constraint perspective, but rather to prioritize moving about within the constraint set in order to develop a more holistic design solution.
- The constraint tool should help to shift focus horizontally within the system, allowing designers to move between highly specific micro-understandings of the system (focusing on the constraints relevant for a single component) and highly general macro-understandings of the system (focusing on the constraints that exist at the intersection of the artifact and the user). Providing designers the ability to shift perspectives in this way will result in a richer understanding of the constraint space, and can lead to new ideas and problem formulations. Highly successful designs balance constraints, and provide benefits, at every system level—something that can only be achieved by relentlessly shifting perspective within the artifact system.

6.3.3 Bring Clarity to Tightly Coupled Artifact Systems

Developing an accurate picture of the constraint space is possible only through understanding the relationships and interactions that exist within and across the five categories of constraints. By taking multiple perspectives and decomposing the system in different ways,

the artifact system becomes more accessible for both research and design. However, an understanding of the interactions that exist both within and across these various perspectives is necessary. It is these interactions which ultimately give rise to the system's actual behavior, just as they are the reason that an artifact's performance is so difficult to predict prior to its introduction. Accordingly:

- the constraint tool should help designers to recognize the interactions and relationships that exist between constraints within and across different system decompositions. It should bring clarity to the way in which constraints affect one another, and in turn the design of the artifact.
- the constraint tool should also aid in the recognition of important trade-offs that exist within the constraint space. Constraint trade-offs are frequently one of the most important aspects of any design process, but in order to design solutions which effectively balance these trade-offs designers must first recognize their existence. The constraint tool should increase the likelihood that designers recognize all of these trade-offs before their effects are felt.

6.3.4 Support the Understanding of Change

Change is pervasive within complex artifact systems. Constraints change with respect to a dynamic environment, the designer's understanding of the constraint space grows, and design changes ripple through the system. Accordingly, the constraint tool must encourage designers and organizations to recognize important constraints, and to collect data with regard to how they change over time—tracking and anticipating change. It should encourage designers to identify important constraints and collect appropriate data that might otherwise be neglected. In fact, it may serve to expose a "…lack of appropriate data collection and integration…" [271] within a design organization. In this way, the tool can spur continued learning and act as a platform for constraint management with respect to a specific artifact and market.

- With respect to the full constraint space, the tool should serve as a knowledge base, helping to understand and explore a particular context, technology space, user group, or an organization's own manufacturing capabilities. Once this knowledge is established it

can be repeatedly leveraged in the creation of new artifacts, platforms, and other innovative activities.

- During the development of a concept, the constraint tool should act as a tool to help designers anticipate the effects of change. Change with respect to a specific constraint can cascade through the system as the result of both intended and incidental connections among constraints. By highlighting these interactions, the constraint tool can provide foresight about how design changes will affect other parts of the system.
- With respect to an artifact's performance over time in a dynamic market setting, the constraint tool may also provide clues about future directions, research opportunities, and failure points, thereby opening new avenues for future inquiries, smarter re-designs, and subsequent variants of a product.

6.3.5 Encourage Collaboration across Teams and Perspectives

Due to the complexity of artifact systems, and the multitude of potential perspectives which they embody, it is likely that design processes which work across stakeholder perspectives and disciplinary boundaries will perform more effectively than those rooted in a single perspective or discipline [272]–[274]. Accordingly, the constraint tool should be designed to encourage collaboration, teamwork, and transdisciplinary activity whenever possible, thus helping designers to develop a shared picture of the constraint space, and allowing them to explore it in ways that are more effective than a single, limited perspective.

- The constraint tool should provide a platform for collaboratively exploring and communicating alternative perspectives, constraint focuses, design tracks, and architectures. If the constraint tool is populated collaboratively—by often-disconnected individuals, teams, or perspectives—it may help to build a shared understanding and increase buy-in across an organization.
- One of the struggles in managing complex design processes is that all of the activities, often conducted by disparate individuals or teams, must converge into a single mutually satisfactory solution. This often requires detailed knowledge not only of the individual tasks, components, and goals, but also the interactions that exist between them.

Constructing and deploying the constraint tool should help to facilitate this connected, multi-level understanding.

6.3.6 Be Useful and Relevant for Actual Design Activities

Finally, the tool must be useful and relevant to *actual designers* participating in *actual design activities*. Theories and models of the design process are certainly relevant, but ultimately every design discipline is about putting ideas into practice. *Actual design*, whether in the context of practice or education, is focused on doing, making, and creating. As a result, the constraint tool must provide value to real-world designers, and design educators, engaged in authentic design activities. The actual underlying value of the constraint tool may vary across design settings, contexts, and practitioners, but in each case it must further the overall purposes of the design activity. More specifically, the constraint tool:

- should be useful regardless of the type of design activity, or the scale at which the design activity is occurring. It should provide value to engineers, industrial designers, architects, or software designers, whether designing highly specialized components or complete systems. Even at the level of the detailed design of a single component, this tool should provide value in helping to manage, track, and understand the interactions of design decisions with respect to intrinsic and extrinsic constraints.
- should be useful to practicing designers and design managers, acting as a source of organization and inspiration. By aiding designers in understanding and exploring the structure and interactions of the underlying constraints, it is possible to recognize new opportunities and problem formulations. This same understanding will help to assess the impacts of design decisions, and how they affect other parts of the artifact system. Recognition of interactions and trade-offs may also help designers to better anticipate sources of potential difficulty and failure prior to their occurrence.
- should prove useful to design educators. In addition to helping educators highlight the importance of constraints, the tool is a tangible way to encourage the exploration of the full complement of constraints—rather than focusing on one, or a few, of the constraint categories. The same is true for the exploration of both intrinsic and extrinsic

constraints: the tool should encourage students to explore constraints relevant to the design's internal structure and components, as well as the design's relationship with the larger artifact system. The tool may also provide a teaching opportunity with regard to the relevance of trade-offs and interactions within a design space.

6.4 The Development of the Concurrent Constraint Management Tool

In order to build upon the existing tools and address the given goals, the *concurrent constraint matrix tool* was developed. This tool is largely built upon the framework established by the Design Structure Matrix, but intends to broaden its influence and increase its practicality for designers confronting real world design problems. It does so by building upon the concepts and strategies of each of the discussed methods, as well as by leveraging the principles and properties of complexity covered elsewhere in this dissertation.

Further, the constraint framework is leveraged in order to provide additional structure, and increase the accessibility of the tool. The recognition of an underlying constraint framework can encourage design teams to understand and explore product systems in a deeper way, focusing on each of the constraint categories. But this is merely a conceptual structure for understanding and exploration, and offers little in the way of actual analysis or practical application. The concurrent constraint management tool (CCMT) builds on this framework and the previous tools. It was designed in accordance with the six goals listed in the previous section, and is intended to provide clarity to the complex set of constraints which underlie any specific design problem.

The CCMT was designed over the course of eight iterative design cycles that occurred over the course of one year. Throughout that time, the key principles were used as guideposts. These principles provided a basis for evaluation as well as an impetus for future design decisions. As with any design process a considerable amount of learning occurred through the creation of working prototypes. Each iteration was tested in a small scale implementation that involved populating the matrix based upon an existing product. These implementations provided valuable information about what worked and what did not, as well as brought to light new opportunities that the tool might be able to address in the future. It is also important to note the many constraints imposed by the actual creation and programming of the tool. Many of the features

were forced to be "dialed back" from their original vision in pursuit of a tool that balanced functionality with practicality—the tool needed to be feasible and able to be programmed given the scope and limited resources of the project.

In all of its iterations the CCMT intends to allow designers and organizations to better understand and explore the holistic set of constraints. By doing so, the CCMT can aid in the design of various types of artifacts. One of the primary functions of the CCMT is to display and quantify the relationships that exist among constraints in a visual, compact, and analytically viable format. By better understanding these interactions it is possible to direct design activities, explore alternative design tracks, recognize critical interactions, and anticipate the effects of design decisions and changes. This section will outline the structure of the tool, and connect each component to its potential value in managing complex design activities.

The CCMT is intended to perform in ways that would not be possible if it was merely a pen-and-paper tool, or even a spreadsheet. Accordingly, the CCMT has been developed as an interactive program intended to assist teams in applying these ideas to real design problems. In order to provide this interactive functionality, the current version of the tool has been programmed using Visual Basic in Microsoft Excel. Rather than being developed as a stand-alone tool—which would have required the program to be coded from the ground up—it was constructed within the existing confines of Excel. This was done in order to take advantage of the functions that Microsoft's spreadsheet program already does well by leveraging Excel's powerful Visual Basic application protocol interface, which is a highly effective library of functions that are quite useful for manipulating spreadsheets and matrices. Developing the CCMT in Excel has the added benefit of building on engineering students' previous experience with this software package, allowing them to quickly familiarize themselves with the tool.

Two separate versions of the CCMT tool were created in order to run within both PC and Macintosh versions of Microsoft Excel. The CCMT tool functions identically across the two platforms, except for some of the stakeholder functionality (discussed in more detail in the following sections) that is incomplete in the Macintosh version of the tool. The complete functionality of the stakeholder module is reliant upon Microsoft Active X in order to manipulate the stakeholder object and register for inputs, but Active X is unavailable on Mac OSX. While this limitation precluded the possibility of producing identical versions of the tool, it

does not affect its core functionality or invalidate its operation. The Visual Basic code for both of these programs can be found in *Appendix A*.

In an effort to further support the functionality and value of each of the CCMT's component parts, portions of this chapter will be supported with student responses gathered during a research study conducted on the implementation of the tool. This research study consisted of two implementations of the tool (across two semesters) within the context of an engineering product design class at the Ohio State University. The CCMT was used by students in a design project that stretched from initial design research (in which applied ethnographies and user interviews were used in a real-world setting in order to identify a design opportunity) to the generation of a design concept and a communication prototype. The student responses included here were recorded in a series of surveys distributed over the course of the project (*Appendix B* and *Appendix C*). This study and its results are analyzed and discussed much more thoroughly in *Chapter 7*.

6.4.1 Developing a Holistic Constraint Understanding

At its core the CCMT is a modified square matrix, or an N^2 diagram as similar tools are called in the systems engineering domain. While N^2 diagrams are typically populated with components and interfaces [141], [275], the CCMT is populated with the *constraints* that are assumed to be relevant to a given design problem. The matrix itself has identical row and column labels, each of which represents a specific design constraint. For ease of directing efforts and encouraging exploration of the full constraint space, the matrix is initially broken down into the five categories of constraints outlined in *Chapter 3*: physical, technological, market, usage, and socio-cultural. The constraint labels are listed horizontally on the left hand side of the matrix with a corresponding identifier—which is used to identify the same constraints along the top of the matrix.

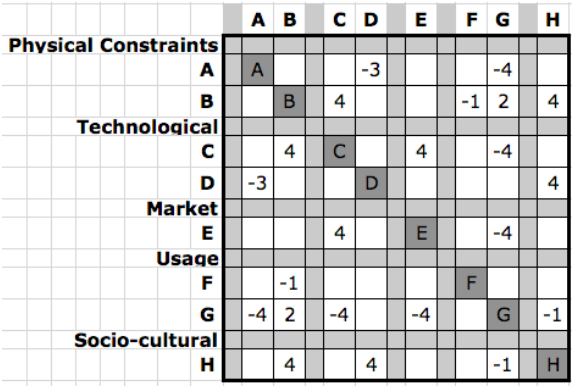


Figure 6.6: At its core, the CCMT is an NxN interaction matrix broken down into five constraint categories.

For the remainder of this chapter, two primary example CCMT matrices will be used: a simplified CCMT matrix which can be seen in *Figure 6.2*, and an example CCMT matrix populated with respect to a DSLR camera, which can be seen in *Figure 6.3* (*Appendix D*). It must be noted that these matrices are populated for illustration purposes, and are not associated with any specific design exercise. The DSLR example matrix in particular is not associated with any study of a real-world camera design process. Nevertheless, the information contained within the DSLR example is intended to accurately reflect the constraints that exist within that artifact system. Because of the author's distance from the actual camera design process, it is not likely to be perfectly reflective of the actual constraints, but it will adequately illustrate the core concepts.

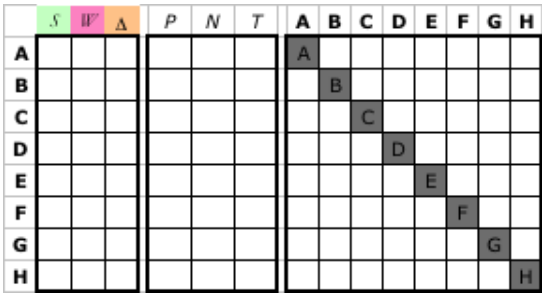


Figure 6.7: A simplified CCMT matrix will be used to illustrate the matrix structure.

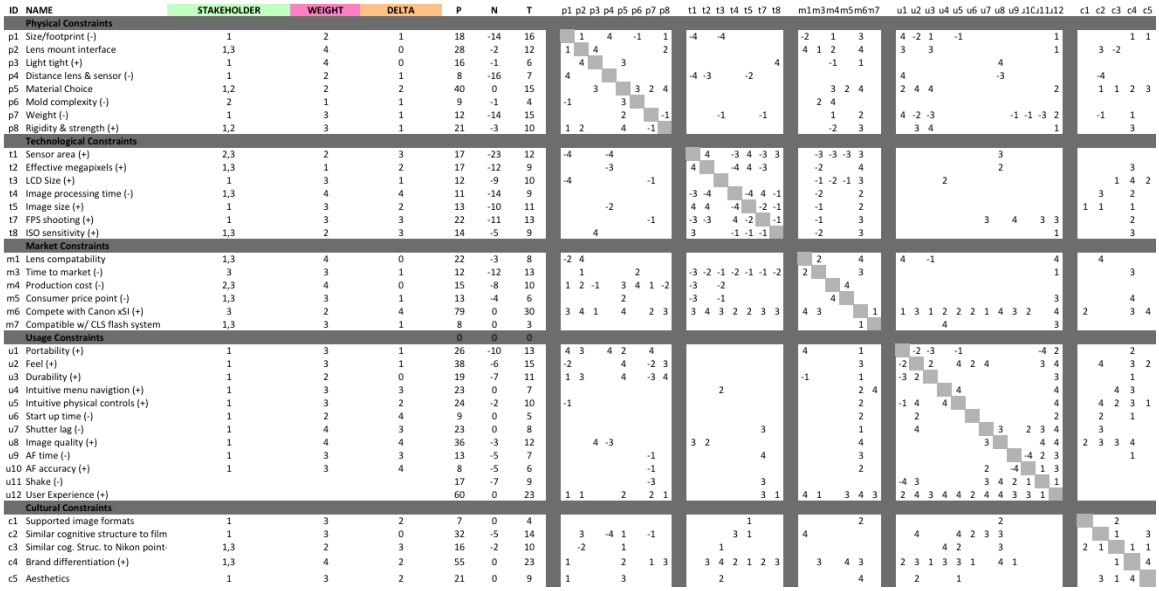


Figure 6.8: A CCMT matrix in Microsoft Excel populated using a DSLR camera example.

The CCMT begins with constraints. Constraints are at the heart of every design problem, and can be used to adequately describe the full range of factors that are significant with respect to the larger unit of design. Accordingly, the *constraint column* captures the constraints that are currently recognized by designers. It is initially divided into the five constraint categories; designers further populate these fields as they see fit. Dividing the matrix in this way encourages design teams to explore *all* of the relevant constraints, rather than focusing solely on their own areas of expertise. Engineering designers may be most comfortable with physical and technological constraints, just as industrial designers may be predisposed to focus on usage and socio-cultural constraints; the inclusion of all categories encourages the team to explore constraints originating throughout the system. Without intending to do so, designers may focus on the constraints in a disproportionate way that is unrepresentative of the actual constraint space; the constraint column forces exploration of all five categories of constraints. This is particularly true in educational settings where students are frequently biased toward one particular part of the constraint space based upon their own limited experience and education.

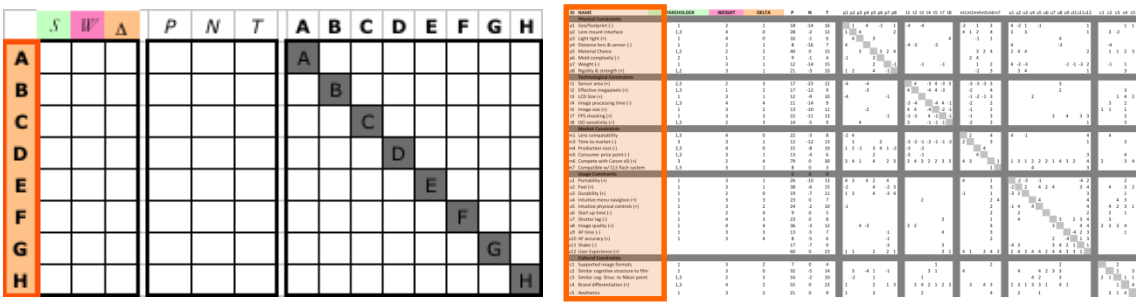


Figure 6.9: The location of the constraint column in the simplified and full matrices.

Later implementations of the tool could redefine these categories or do away with them entirely, but in its current state delineating these categories has the benefit of visually drawing attention to constraints categories that are less than thoroughly explored. An unbalanced matrix, with considerably more entries in one category than all the others, draws attention to the designer's (or design team's) own biases and predispositions, and can give direction to future research and design effort. The structure of the matrix, broken down into these five primary categories, encourages designers to populate the matrix across all of the categories—stressing a more holistic exploration of the constraints. One student noted: "[The tool] …made us think outside of the track we were currently in….Going back and seeing the constraints helped us rethink things."

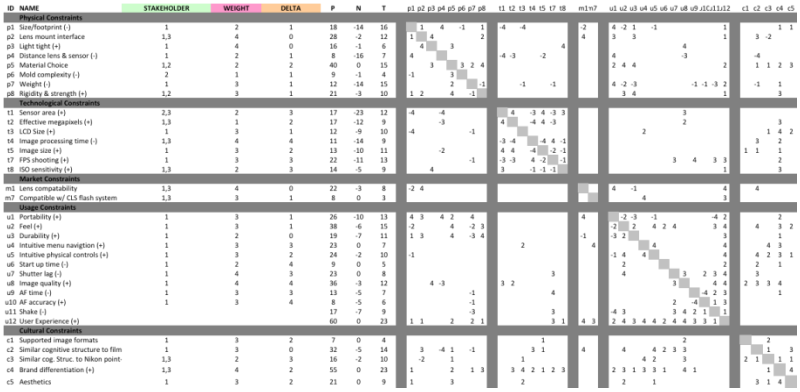


Figure 6.10: An under-populated constraint category can visually draw attention to part of the constraint space that has not been adequately explored.

There is also considerable benefit to simply populating the constraint column, as it forces designers and teams to explicitly acknowledge the constraints. Simply recognizing and articulating the constraints on a design can have real value within the process. This was an aspect of the tool frequently recognized by the student participants: "…just taking the time to specifically think about each constraint for our product helped us visualize our product and how it functions much more." And, "I like it kind of like a whiteboard [sic]. It helps to organize your ideas together and makes you actually 'say' what the constraints are rather than just going along without defining them." One student cited the CCMT as the reason for identifying previously unrecognized constraints on a design: "It made us think about some contraints [sic] that we did not think about at first. This made the group go back and create new features to over come these contraints [sic]."

Additionally, when the CCMT is used for large and complex design activities, the constraint column is intended to encourage the centralization and organization of relevant factors that originate from often disparate points within the product system. In this way, it can act as a helpful project management tool, aggregating constraints that arise from design, management, manufacturing, and any number of other locations within the system. This central store of constraints can be maintained and modified throughout the process in order to better match designers' understanding of the problem. While the classroom application is limited in its scope, another student stated: "Our design problem consisted of many different issues. The challenging part was trying to figure out which ones to really focus on. We accomplished this using the results from our survey along with the constraint matrix. These two items helped take a lot of seemingly little issues and group them into main themes and see how they are all related (and unrelated)…. Having all of the data and constraints on a long laundry list does not make it easy to sort through and prioritize, but the constraint matrix helped us figure out what was really important and do-able for the final design."

6.4.2 Tracking Interactions and Trade-offs

The *interaction matrix,* created by the intersection of the included constraints, captures the relationships and dependencies that exist between them. Shaded cells, representing the intersection of each constraint with itself, bisect this matrix diagonally. Every constraint

interaction that does not exist on this diagonal can be populated in accordance with the estimated *strength of the interaction* between the two corresponding constraints. For example, weight and portability are two constraints that are likely to interact strongly in the design of a DSLR camera. There is a clear relationship between these two constraint factors, which is reflected in the body of the interaction matrix at the intersection of the weight and portability constraints. There are two cells within the matrix that represent this interaction, one on each side of the diagonal, and because the relationship occurs when viewed in both directions—weight has an effect on portability, and the portability constraint has an inherent effect on the camera's weight—both cells can be marked to indicate that interaction. A similar process can be conducted for every other pair of constraints within the matrix.

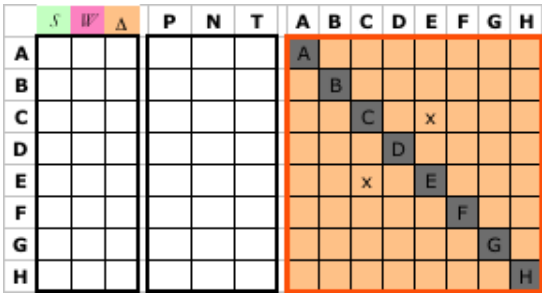


Figure 6.11: The CCMT interaction matrix tracks interactions between two constraints.

Much like the constraint column, simply populating the interaction matrix holds a great deal of inherent value. First, the activity of populating the matrix forces designers to consider how constraints interact with one another. As each row/column of the CCMT is populated, the intersection with every other constraint presents itself for consideration. This draws further attention to relationships that may need to be considered or investigated, and encourages a deep exploration of the complex problem. The interaction matrix is useful in that it can direct attention to many interactions which might never be considered otherwise—particularly those relationships that exist across disconnected parts of the system or between units within an organization. One student said, "I think there is some impact in the fact that it caused us to think about how different constraints interact with each other." And another stated that, "I think it makes the designer have to think about all the constraints ans [sic] how they might interact with each other. This is very important in design."

The actual interaction values can be populated using any numerical scale. It is important to recognize, however, that there is no 'correct' scale. Interactions can be quantified in any manner seen appropriate by the design team. So long as the scale is held consistent, there is little difference between a scale which judges interactions between '0 – 100', '0 – 10', or '0 – 4', the primary difference being the gradation within the rating scale. In many instances, assessing nuanced differences between the strength of two constraints' interaction may be quite difficult—the difference between a 75 and a 76 is quite negligible. Instead, what is critical to identify is the relative strength of the constraint interaction. For example, it is important to recognize when there is no interaction, a significant interaction, or a strong interaction. Frequently, anything more detailed than this offers little in the way of actual value. But these interactions can still take on any value the practitioners elect to give them—in case it is useful within a particular design context.

While the chosen scale may not be critical to the CCMT's application, it may be useful to distinguish between positive and negative interactions: Positive values indicate a positive correlation between two constraints where improving one likely improves the other. Negative interaction values indicate situations in which a change with respect to a single constraint is likely to have negative consequences on another. These high value negative interactions direct designers' attention to potentially problematic interactions and conflicting design goals and requirements. Increasing the strength of the material of which the camera body is made, for instance, is likely to have a negative correlation with respect to constraints relating to material costs and the cost of production. High-value positive interactions, on the other hand, can be seen as potential leverage points or opportunities, in which addressing one constraint is likely to positively impact another. Increasing the strength of the material is likely to increase the durability of the camera in the eyes of photographers. Thus, a populated CCMT increases the design team's recognition of both potential pitfalls, and opportunities for efficient design improvement.

In these instances, there is a large difference between positive interactions which may provide benefits based upon design changes, and strong negative interactions which frequently signify difficult trade-offs within the constraint space. These trade-offs are extremely important to recognize and anticipate because they represent critical decisions which must be satisfactorily balanced within the final solution. Failure to recognize these interactions can lead to potential

shortcomings with respect to the total artifact system—whether those shortcomings are unforeseen difficulties, unexpected manufacturing costs resulting from the choice of a stronger material, or insufficient durability to withstand the rigors of photographic use. Populating the CCMT not only encourages recognition of these constraint interactions, but also provides increased visibility to these important interactions for the duration of the design process. In this way, the CCMT can serve as a sort of knowledge base over the course of the project by helping to maintain awareness of the ways in which the underlying constraints, goals and requirements may be affected by future design decisions.

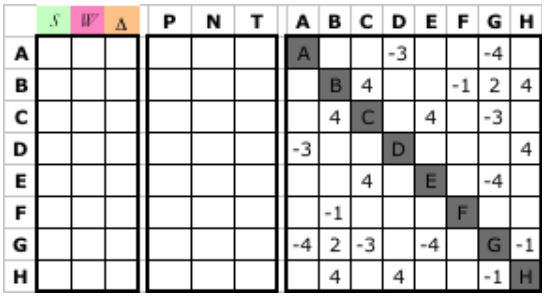


Figure 6.12: CCMT matrix with both positive and negative interaction values.

Looking at the entire matrix, designers can quickly identify the important trade-offs with respect to each constraint. These trade-offs are critical because identifying and addressing constraint trade-offs is a critical part of design. In design, there are certainly times when constraints do not go head–to–head with one another—where trade-offs are diminished. In these instances, addressing these constraints is not particularly difficult. The real challenge of design lies in addressing constraints that at first blush do not work together at all. Finding a way—through creativity, intuition, analogy, and persistence—to produce an ensemble that satisfactorily addresses as many of the constraints as possible, is the primary challenge of design.

The CCMT intentionally draws attention to these critical interactions within a design. Suppose a team applies a CCMT in which interactions are ranked on a scale of '-4' to '4' (where '-4' represents a strongly negative interaction or trade-off and '4' represents a strongly positive synergy between two constraints): Essentially, addressing the constraints in which the rows are populated with mostly 0's and ±1's is comparatively easy. That is not to say that there is not an

extensive amount of work involved with identifying the appropriate way to address these constraints, as there may be countless ways to address this single constraint. But given an adequate level of skill, designers are likely to find one that will suffice. What separates adequate solutions from truly great ones are situations in which a design is able to balance constraints that are seemingly incompatible—those which embody difficult trade-offs. Good design is all about identifying and mitigating the '-4s' and leveraging the '+4s' in order to identify innovative solutions. Identifying these trade-offs and leverage points will aid designers in anticipating the effects of changes to the artifact's design, provide better foresight about how designs might fail, and help designers to identify new directions in a complex design space.

While both negative and positive interactions can easily be tracked, in most instances the negative interactions are the most important. By recognizing the location of these trade-offs within the system, organizations can better monitor the most sensitive portions of their designs. Within the design process, it is important to understand the implications that design changes—made to address some constraint—will have for other parts of the design. One student recognized that, "the constraint matrix is a good tool to force additional thought from the groups to consider different problems that may arise in the design process." And another stated that, "I think it was generally helpful, best for forcing the designer to articulate exactly what the boundaries are and the issues to address, preventing oversights from popping up as problems later."

This is immediately evident for intrinsic constraints—making an artifact larger, all other things held constant, will make the artifact heavier—but we must also understand how these changes affect other extrinsic constraints. Understanding how changing an artifact's physical size affects its usability, its perception, and its manufacture are every bit as important as understanding the purely internal implications. These external implications are often harder to recognize and track because they are more loosely connected—a result of the decomposable nature of artifact systems. The CCMT, however, seeks to provide early recognition of how design changes will affect other parts of the system, both internal and external to the artifact. The CCMT is designed to help identify these issues pre-release, recognize them more quickly post-release, or design in measures that allow them to be addressed after release—designed modularity to facilitate the repair of a particular component, for instance.

Alternatively, recognition of high value, positive interactions can provide designers with insights relative to the best leverage points within a design. How can we make design changes that will efficiently benefit multiple high value constraints? If we can identify central constraints which are positively correlated with other high priority constraints, it may be possible to make a single design change which positively affects multiple parts of the artifact system—simultaneously reducing costs and improving functionality for the end user, for instance. Identifying these points within the system may allow organizations to provide additional effort and exploration to these areas in order to identify new directions and potentially innovative solutions. Discovering these high value interactions and trade-offs also signifies that significant coordination and communication may be required. This is especially true when these high value relationships exist between constraints that are the responsibility of disconnected teams and disciplines. If there is a high value trade-off between the aesthetics and some aspect of the artifact's manufacture, the artifact's design and fabrication would likely both benefit from increased communication between designers and manufacturing engineers.

More functionally, the interaction matrix also acts as what Tom Ritchey calls a "garbage detector" [276]. The CCMT can direct designers' attention to 'garbage' in the form of vague constraints, duplicated constraints (different constraints that identify the same thing), overlapping constraints, and constraints that mean different things to different individuals, just to name a few. These issues are often brought to light when it is difficult to understand, or assign a value to, the interaction between two corresponding constraints. Recognizing these issues forces designers to revisit their initial formulation in order to review the constraints, and thus encourages constraints to be added, removed, and redefined in order to improve the functioning of the CCMT. A set of constraints refined in this manner is likely to be more accurate with respect to the actual nature of the design problem, and in turn improves designers' understanding. While there is no single right or wrong way to formulate the constraints, this revision process also reduces confusion originating from improperly defined constraints, and improves the CCMT's usability.

6.4.3 Shifting Perspectives and Building Anticipation

On the left side of the matrix there are three supplementary columns created to capture additional information about the constraints themselves. These columns are intended to help designers more accurately capture and reflect the actual structure of the design space. The stakeholder column *(S)* allows designers to associate individual constraints with specific stakeholders. The relative importance *(W)* allows designers to associate weights with each individual constraint. The final column is used to track the expected rate of change *(Δ)* for each constraint, allowing designers to identify the constraints most likely to change—causing failures or requiring future design efforts.

The *stakeholder column*, appearing directly to the right of the constraint column, identifies the stakeholders to which each individual constraint is most relevant. This designation allows designers to associate individual constraints with their points of origin. For example, 'mold complexity' can be associated with manufacturing, 'image quality' can be associated with photographers, and 'brand identity/differentiation' can be associated with upper management or the design organization itself (Nikon, Cannon, etc.). Additionally, each constraint can be associated with more than one stakeholder in order to better reflect the actual system. There are many instances in which a single constraint is relevant to multiple stakeholders, and the CCMT should reflect that as well. The camera's number of effective megapixels, for example, is relevant to both users and the design organization as it affects image quality and is a competitive metric, respectively. This allows for stakeholders to be listed in a more nuanced fashion. For example, if design researchers have conducted applied ethnography studies with both professional photographers and hobbyist photographers, the relevant constraints can be broken down accordingly, with constraints that are relevant to both types of photographers still being associated with both.

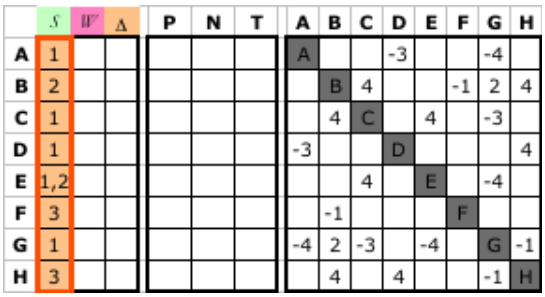


Figure 6.13: The CCMT stakeholder column; note that multiple stakeholder values are applied to constraints 'E'.

The stakeholders themselves are listed separately on a second worksheet within the Excel workbook. Once included on this worksheet, they are automatically populated in a table at the top of the CCMT worksheet. This stakeholder table exists for reference (so that individual constraints can be appropriately identified), but also allows for quicker identification of constraints associated with specific stakeholders. When a stakeholder name is selected in the stakeholder module above the matrix, all of the constraints associated with that particular stakeholder are highlighted (PC only). This allows designers to quickly visually assess which constraints are associated with each stakeholder. Allowing designers to view the constraints relevant to each stakeholder separately can help designers to take the perspective of various stakeholders within the system. If designers want to know what is important from the perspective of manufacturing, they can simply click on 'manufacturing' within the stakeholder module. In this way, the CCMT allows designers to quickly shift perspectives within the complex artifact system. As discussed, taking multiple perspectives is the only way in which to develop a robust understanding of all the constraints relevant to a particular design problem.

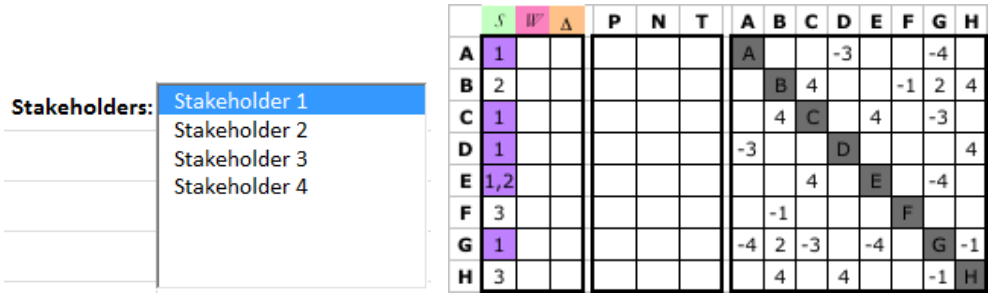


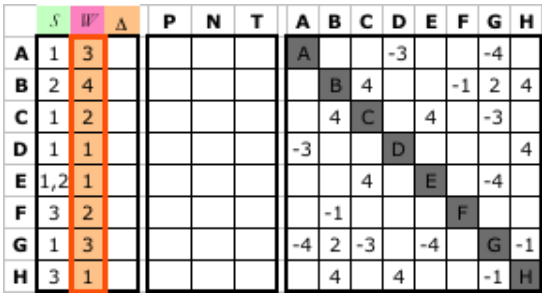
Figure 6.14: Stakeholder module and example matrix with 'stakeholder 1' constraints highlighted.

Allowing individual constraints to be identified in this way also helps designers to more adequately track and monitor these constraints throughout the design process. In turn, this feature focuses designers' attention when monitoring and assessing the current state of a solution with respect to a particular perspective. This capability can also help designers with future conversations with a particular stakeholder. If a designer intends to interact with manufacturing personnel, for example, they can quickly refer to the CCMT for a 'refresher' on the constraints most relevant to that part of the organization. In this way, the CCMT can facilitate collaboration as disparate groups are able to better understand each other's perspectives. The tool also allows this mutual understanding to be maintained throughout the process. At the very least, it helps to reduce redundant conversations that happen between groups by allowing each to quickly refresh their understanding of the other perspective.

Additionally, by clicking on more than one stakeholder within the stakeholder module, it is possible to view more than one stakeholder at a time. Doing so allows for stakeholders to be combined, and permits viewing combined perspectives. Clicking on both 'professional photographers' and 'amateur photographers' for instance, immediately combines these two stakeholders into a single larger class of stakeholder—users, or photographers. Combining stakeholders in this way allows for easy visual recognition and analysis, which can help designers to explore the constraint space in ways that more closely match their current needs and understandings.

In these ways, the stakeholder functionality of the CCMT allows for a more polycentric understanding of the entire artifact system. Thus, the CCMT can help designers to overcome their own local views of the constraint space, and promotes design solutions that are more fit to the factors that matter at every level of the system. It helps to leverage the perspectives of individuals associated with specific parts of the design who are more acutely aware of the constraints related to their part of the system. While this information can be difficult to aggregate, categorize, or even comprehend the CCMT provides a framework within which this is increasingly possible. Accordingly, the CCMT can help design organizations to potentially overcome challenges associated with disparate perspectives, data aggregation, and the currency ('up-to-dateness') of information by leveraging elements of polycentric control as applied to the collection, assimilation, and dissemination of information about the design space.

Moving one column to the right, the *weight column* exists to give priority to the different constraints. The weight column allows design teams to assign relative importance values to each constraint. This column reflects the actual nature of design problems, in which every constraint is not equally important; nor are they given the same priority by designers. Constraints of high importance can be denoted accordingly, providing focus and allowing designers to ensure that these constraints are met satisfactorily. The weight column itself is relatively straightforward, as it is used in many similar tools—from the House of Quality [277] to Pugh charts [5] and morphological analysis methods [6].



	S	W	Δ	P	N	T	A	B	C	D	E	F	G	H
A	1	3					A			-3			-4	
B	2	4						B	4			-1	2	4
C	1	2						4	C		4		-3	
D	1	1					-3			D				4
E	1,2	1							4		E		-4	
F	3	2						-1				F		
G	1	3					-4	2	-3		-4		G	-1
H	3	1						4		4			-1	H

Figure 6.15: The CCMT 'weight' column reflects the constraints' relative importance.

Once these weights are determined, exploring alternative weights for critical or difficult constraints can help designers explore new design directions, problem formulations, or innovation paths. Specifically, by intentionally increasing or decreasing the weight of individual constraints, designers can drastically change the design problem and its solution [278]. The differences between laptop and desktop PCs based upon the weighting of a single portability constraint have previously been discussed.

In the case of a DSLR, it is worth considering what one might look like if designers drastically increased the importance of portability. Cameras like the Nikon 1 and the Olympus PEN E-PM1 are one possible solution to this altered design problem. These cameras share many design aspects with traditional DSLRs, but they depart from them in one major way: not quite a DSLR, these cameras represent a hybrid design offering the portability of many small 'point-and-shoot' cameras with the interchangeable lens interfaces found on larger, more fully featured, DSLRs. While the long term success of this type of camera has yet to be determined, the point is

well made: consciously playing with the relative importance of constraints can lead companies to previously unexplored ground and potentially innovative directions. When these weights are leveraged in conjunction with the interaction matrix, it is also possible to better anticipate how the changes to these constraints may affect the larger system. By following the relationships and trade-offs within the interaction matrix, designers can better envision the effects of potential changes without having to actually confront the realities of implementation, or incurring the costs of fabricating expensive prototypes.

It must be mentioned that individuals using the constraint matrix are likely to disagree more often about the relative importance of the constraints than they are the constraints themselves. Each designer is likely to see the relative importance of the constraints in a slightly different way. Discussion amongst designers may lead to a shared understanding and a more representative weight for each constraint, but it is still highly unlikely that all designers will ever agree on the relative importance of every constraint. In fact, this difference in how designers prioritize constraints represents their own unique constraint focus. Accordingly, these numerical weights should represent consensus opinions rather than a single, best constraint prioritization. They can be used as a starting point from which individual designers can diverge, by formally (in the matrix) or informally (in their mind's eye) shifting the way the constraints are prioritized. When it comes to the actual design of an artifact these weights are a matter of personal preference, to be stretched and shifted as desired. In fact, using different relative constraint weightings might be an effective way to instigate competing designs early in the process.

The next column is the *expected rate of change*, referred to here as 'Δ'. While the idea of weighting constraints is relatively standard across similar matrix based tools, the expected rate of change column is, to the best of this author's knowledge, unique to this tool. Design is a temporal process that is both intent on creating change, and dependent on changes to the constraint space. The CCMT, in contrast, appears relatively static. New constraints can be added or removed, and relationships changed, but the intent of the tool is also to help designers anticipate changing constraints. A stale picture of the constraint space will lead to design solutions that do not fit with the current state of the world. In order to increase awareness of this change, and to better track its effects on the design process, the CCMT employs the expected rate of change column. This column is populated with the design team's best estimate

of how quickly each constraint is likely to change. In *Figure 6.11*, the constraints are rated on a '0' to '4' scale, with '4' representing rapid change and '0' representing little or no change.

	S	W	Δ	P	N	T	A	B	C	D	E	F	G	H
A	1	3	1				A			-3			-4	
B	2	4	2					B	4			-1	2	4
C	1	2	3					4	C		4		-3	
D	1	1	1				-3			D				4
E	1,2	1	1						4		E		-4	
F	3	2	1					-1				F		
G	1	3	4				-4	2	-3		-4		G	-1
H	3	1	0					4		4			-1	H

Figure 6.16: The CCMT 'delta' column allows designers to anticipate the rate at which constraints change.

Certain constraints will remain relatively static over the course of the design process, and over the course of the product's life-cycle. The lens mount interface by which modular lenses can be attached to SLR camera bodies, for example, is highly unlikely to change as manufacturers must ensure that all of their existing and future lenses will work with the camera body. However, there are other constraints—those related to image sensor technology, for instance—which are likely to change much more rapidly. These constraints may change during the course of the design process (for example, as a result of a competitive product entering the market), or as a result of the artifact's introduction into the context of use. The way that these constraints look at the outset of the process, might be very different from how they look at the point of release. The 'Δ' column draws attention to those rapidly changing constraints that should be closely monitored over the course of the design process. The very act of populating this column itself encourages designers to return to these constraints from time to time to assess their accuracy and impact on the design—are they holding steady, or are they changing and shifting the design problem along with them?

If a single CCMT is used over the course of multiple design projects, the 'Δ' column can also suggest the constraints that will be most important to monitor post-release—acting as a reminder of the portions of the constraint space most sensitive to change. In this way, the CCMT can help with long-term product, or platform, management. Recognizing the constraints that are changing the most quickly is important because these are the factors—indicative of

everything from user desires to technology cycles—that will most frequently drive re-designs, product updates, and future products. Essentially, these fast moving constraints are the ones most likely to pace future design activity. Distinguishing these constraints can potentially lead designers and design teams in the direction of more innovative architectures which may better accommodate change, or to novel design concepts and directions generated in response to this change.

6.4.4 Negotiating a Shared Understanding

Building any sort of model necessitates choosing a boundary for the system of interest. In the case of the CCMT this consists of determining which constraints are endogenous and exogenous to the system. A single individual can do this, but doing so in a collaborative interdisciplinary way has clear benefits in addressing complex problems. Rather than relying on a single perspective, designers can leverage the knowledge, experience, creativity, and foresight of multiple individuals (or teams). Populating the CCMT collaboratively forces designers to balance perspectives and negotiate a shared understanding of the design problem by requiring each member of the team to articulate those aspects of the problem that are most relevant from the perspective of their own discipline or organization. Within a design team, this dialogue can expose individual perceptions and biases about which constraints are relevant (constraint column), which are most important (weight column), how constraints interact (interaction matrix), and how constraints may change (Δ column) within a given design space.

It is the intention of this tool that every member of the team is forced to question their own perceptions, and is challenged to learn more about the nature of the design problem. As one student pointed out, "…the constraint matrix is especially useful for multidisciplinary teams, because everyone can bring their expertise in to [sic] building it accurately, and people who may be less knowledgeable in a certain area can use it to understand how the features that they want interact with the features that others want and all can address the problems from a shared understanding of the breadth of issues." Each designer brings with them their own perspective about which constraints are relevant to a given design situation, but populating the matrix in a group setting can help to build a more *complete* perspective of the artifact system. Even this collaboratively constructed model, however, is not the single correct perspective on the

system—it does not represent the only formulation of the design problem. Accordingly, individual designers are free to move within the constraint space in order to explore different constraint prioritizations and solution directions.

At a higher scale within the design organization, the CCMT is intended to encourage similar collaboration across disciplines and organizational units. As any single team is unlikely to have a complete picture of the constraint space, or the expertise necessary to appropriately value every constraint interaction, the CCMT can initiate dialogue among different areas of knowledge: between industrial design and engineering design, for example, or engineering design and manufacturing. By doing so, a deeper, more shared understanding of the design problem is honed, with each discipline and each part of the organization better equipped to recognize and appreciate the challenges, requirements, and mindsets of the other parts of the organization with whom they interact. Involving manufacturing personnel to help populate the constraints relevant to their perspective will not only result in a more accurate CCMT, but will likely have a number of other positive side effects—ranging from increased communication, to designers better understanding the organization's manufacturing and processing capabilities. Strong interactions noted in the interaction matrix provide a clear indication that increased collaboration and communication may be necessary in order to balance trade-offs and reach successful compromises for constraints likely to have strong impacts on other parts of the organization.

6.4.5 Dynamic Highlighting to Direct Focus and Improve Usability

The CCMT employs dynamic highlighting based upon particular conditions. These dynamic highlights are a key part of representing the constraint space in a highly visual, intuitive format. Beyond that, these highlights help to direct user attention and increase the salience of the data. In the Excel program, the currently active constraint row is highlighted in the color blue, allowing for easier focus within the spreadsheet. This highlight, which moves with the cursor, also improves the ease with which users can populate the interaction values. When the active cell is located within the interaction matrix, this blue highlight is echoed in the constraint ID row at the top of the table in order to help users identify the active row and column (the intersection between two constraints). As a user moves the active cell within the matrix, the constraint on

which the CCMT is focused also changes, and the blue highlight moves accordingly. This helps to avoid confusion associated with reading data within a large matrix.

Figure 6.17: The blue constraint highlight indicates the currently active row—shown in both the example and full matrix.

This highlight helps with the readability of the matrix, but may be even more valuable in populating it. As the blue highlight immediately shows the active row and column, the matrix can be populated by simply moving vertically within a constraint column. The easiest way to do this—which was identified by a number of students—is to place the cursor on the main diagonal of the constraint whose interactions the user wishes to populate. At this point, the constraint of interest will be highlighted (constraint 'C' for instance). Moving the cursor up and down this *column* (C) then allows a user to populate the interactions with the other constraints; as a user moves the cursor down a *row*, the paired constraint's *name* will now be highlighted. This allows for easy verbal recognition of the relationship being evaluated. This is in contrast to reading across a row and, with each new cell, tracing the interaction upwards to the column identifier, which must then be associated with its constraint name in order to valuate the relationship. In this way, the active constraint highlight allows a user to quickly and easily populate all of the interactions for a given constraint—simplifying a previously tedious process.

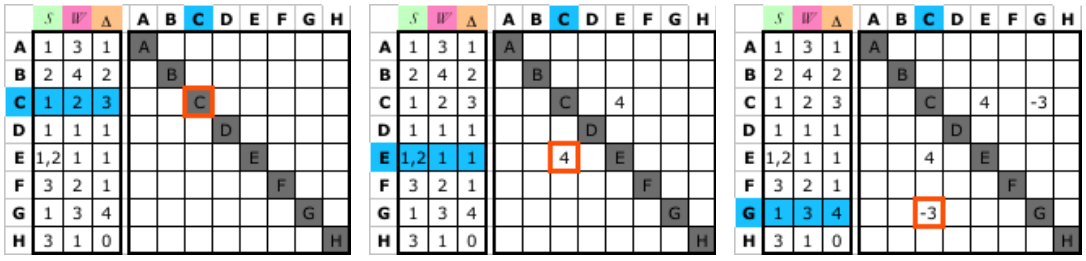


Figure 6.18: Populating interaction values for constraint 'C' by moving down the column.

Further, additional dynamic highlights within the matrix help draw designers' attention to important relationships within the constraint space. The *interaction threshold module* allows high value interactions to be more easily identified amidst the large amount of data within the interaction matrix. Once a threshold value is set (in a field above the matrix), all of the interactions which meet (or exceed) this value will be highlighted within the active constraint row, and within the corresponding column. This value can be set to any value the user desires, which allows this module to work in conjunction with any chosen scale. If the chosen interaction scale goes from 0-4, setting the interaction value at '4' will dynamically highlight only those interactions of the highest magnitude within the currently selected row. Changing the interaction threshold value to '3' will highlight all interactions of rank '3' and rank '4'.

Doing so increases visual recognition and better directs focus to the important interactions and trade-offs within the constraint space. In order to further improve the readability of the matrix, all of the interacting constraints are highlighted both in the body of the matrix and in the constraint column. This means that each interaction need not be traced back up the columns to determine its identity—users can simply read down the 'constraint column' in order to see which other constraints the selected constraint interacts with. Both negative and positive interactions can be highlighted, with differently colored highlights to help users to quickly differentiate between the two. Additionally, the threshold values for negative and positive interactions can be set independently, allowing the user to tailor the information that is visually emphasized. Once any constraint is selected, this feature allows designers to identify important trade-offs and potential leverage points at a glance.

(-) Interaction Threshold:	-3
(+) Interaction Threshold:	4

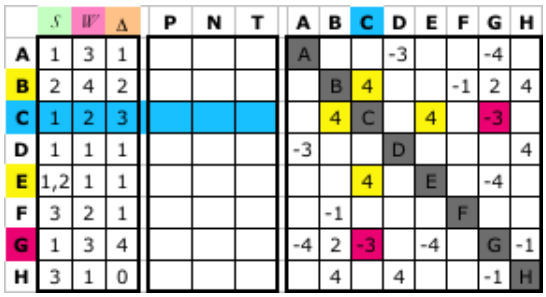


Figure 6.19: Constraints 'B' and 'E' can be easily seen to positively interact with constraint 'C'. Constraint 'G' interacts negatively (with a threshold of '-3').

These constraint interactions are highlighted for the active row only, in order to improve focus and increase the readability of the matrix; this can best be seen in contrast to a matrix which highlights all high-value interactions. Highlighting all of the high value interactions throughout the entire table was considered and attempted, but highlighting a single row was preferred. This is because doing so highlights numerous cells throughout the matrix, which does not adequately direct the user's attention. Highlighting only the constraints relevant with respect to a single constraint better directs focus, and makes the data more digestible. It is frequently difficult to consider all of the high value interactions in the table simultaneously, and only showing the high value interactions for a single active row forces users to consider the constraint interactions in a more detailed way. Still, there may be value in viewing a fully highlighted matrix, particularly with respect to visually analyzing the full constraint space. Therefore, the ability to do so should be preserved moving forward.

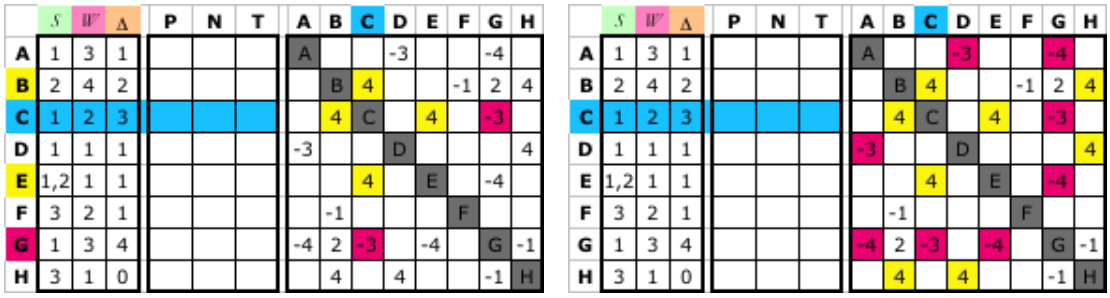


Figure 6.20: Even on the simple CCMT, it is possible to see how focus can be lost by highlighting the high-value interactions for an entire matrix.

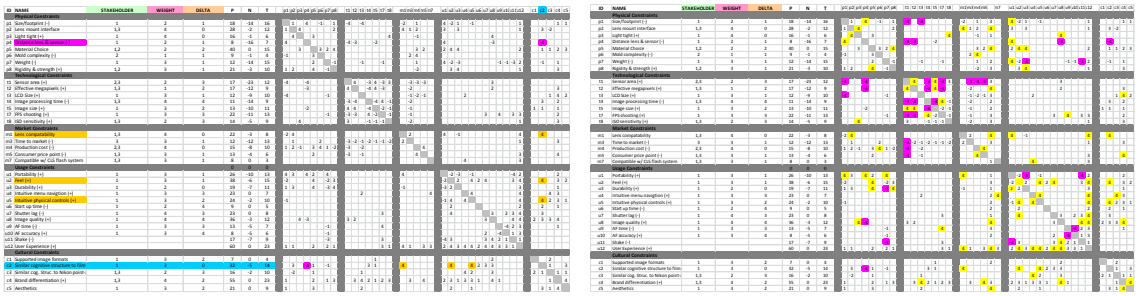


Figure 6.21: The confusion of highlighting every high-value interactions is amplified when viewing a fully populated matrix.

6.4.6 Second-order Interactions

The CCMT helps designers to track and anticipate unexpected interactions through its ability to highlight second-order interactions. These second-order interactions highlight the constraints which are not directly affected by the active constraint, but which may be affected as the result of a chain, or cascade [16], [70] of high-value interactions. These are the constraints that strongly interact with strong first-order interactions. When this feature is toggled on using the *interaction depth module*, second-order interactions are highlighted in a lighter shade. This module can be used to track positive and negative second order interactions independently, or both simultaneously, based upon the input values. Syntactically, what is occurring is that the program is running the same procedure in a twice–layered fashion. If the depth is set to '1', the program reads through the active constraint row and highlights every interaction which meets the threshold value. Once the depth is set to '2', the program runs the algorithm a second time for each of the first-level interactions, thus showing all of the second-order interactions so that designers can view the chart and note potential points of influence, which might not otherwise be recognizable at a glance.

(-) Interaction Depth:	2
(-) Interaction Threshold:	-3
(+) Interaction Depth:	2
(+) Interaction Threshold:	4

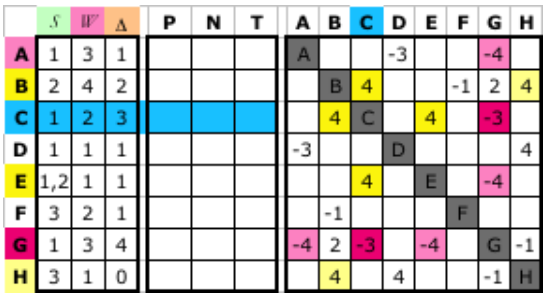


Figure 6.22: The interaction depth module can be used to track both negative and positive interactions.

In *Figure 6.17*, one can quickly identify 'B' and 'E' as first-level positive interactions, as they interact directly with constraint 'C.' But 'B' interacts with other constraints, and a change to 'C' therefore has a chance of affecting 'H' as well—despite the fact that this constraint does not interact directly with 'C.' This is recognizable in the interaction matrix, but more easily seen by scanning down the constraint column. Looking at potential trade-offs, 'C' interacts with 'G' at the threshold value (-3). 'G' in turn interacts in a strongly negative way with 'A' and 'E.' Therefore, changing 'C' may have unforeseen negative effects on these indirectly related constraints. This makes the process of understanding and exploring the structure of the constraint space easier, especially for the second-order interactions which might otherwise go unrecognized and unheeded.

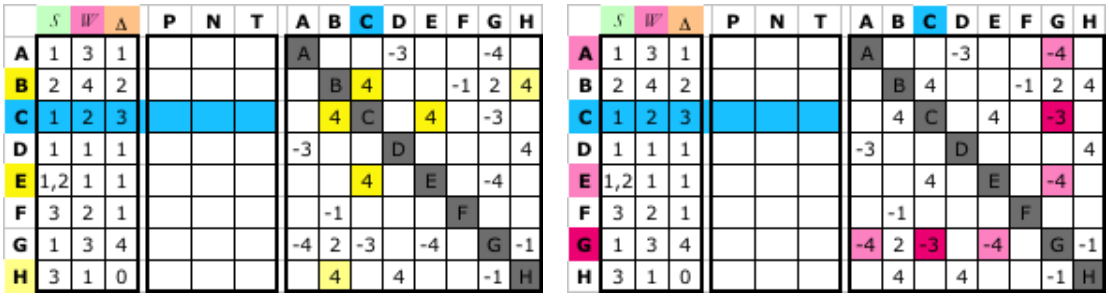


Figure 6.23: The CCMT can track both positive and negative second order interactions independently.

While experienced designers and organizations would be expected to recognize first–level interactions, secondary interactions and effects are considerably more difficult to recognize and anticipate. The majority of emergent problems arise as the result of changes that cascade

through the system—with one design decision affecting some constraint, which in turn affects another constraint, which in turn affects another. All complex artifact systems are composed of trade-offs, on top of trade-offs, on top of trade-offs. Navigating this tangled web of interactions is incredibly challenging, but is often necessary in order to achieve good designs. While designs can certainly achieve success without detailed analysis of these factors, bringing attention to these relationships can only increase the understanding of the system and help to build anticipation—both of which increase the likelihood of developing artifacts more fit to the full complement of constraints. The CCMT confronts this problem through a combination of the interaction threshold module and the interaction depth module.

Still, the CCMT only tracks direct interactions between constraints; the behavior of the full system is still dependent upon non-linear interactions that may never be captured in the tool. The CCMT is, admittedly, not a complete model of the system in which every single interaction and behavior can ever be modeled. Employing the CCMT does not ensure full comprehension of the system, and it cannot hope to completely eliminate surprise from the equation or predict every emergent behavior. At the same time, even recognizing these direct interactions can provide greater foresight about the effects of altering a design—helping designers to recognize and address potential issues before they occur. Suppose, for instance, that changing an artifact's form slightly leads to a major, and expensive, change in the current mode of production. Recognizing this at the time of the design change, rather than in pre-production can result in sizeable savings of time and money.

The students who employed the CCMT recognized this aspect of the tool. With respect to building anticipation about how design changes would affect the full artifact system: "The matrix helped us understand better what constraints were important, and how changing them would affect the rest of the design"; and "I think that when designing and deciding, we referred to the constraint matrix. It's a good visual tool to see interactions. In the future, if we were to make changes to the product, I feel like this tool could be very helpful." Some students even noted the impact that the tool had on the direction of their project: "We took quite a bit of time to go through the constraint matrix and specifically fill out all we could and take the time to think about how each constraint applies to which to see how each change affects which. We ended up filling out a matrix twice because our design changed considerably and filling out the matrix the first time helped us to understand that we needed to change our design around a lot."

Even some students who did not find the tool particularly useful saw the matrix's potential to help anticipate change. One student in particular noted its potential value during redesign efforts saying, "I don't hate nor love it.... It's a tool that didn't have much relevance in our final design, in my honest opinion. Not that it wouldn't in the future, because I feel like it will be important to redesigns (i.e. if we change X, how will this affect Y and Z?)."

6.4.7 Connectivity Measures

At a glance, the CCMT interaction matrix can be overwhelming and difficult to parse. Looking at the complete matrix, it is difficult to quickly gain a sense of which constraints are the most integral to the structure and operation of the artifact system. In order to make this assessment more accessible, one student team added a column at the end of the matrix which summed up all of the interaction values within every row. They stated that, "it would be a good addition to the matrix if the rows and sections were summed at the right side. That way, we could easily see which category is the most important!" Summing the interaction values along a row represented a quick heuristic which allowed them to quickly assess which constraints were the most highly connected within the matrix.

This particular implementation, however, can be developed further. By adding three columns to the matrix, instead of one, it is possible to more accurately capture information about which constraints are the most connected, which hold the most potential, and which may be the most problematic. Of these *connectivity columns*, the first sums the positive scores within a row ('P' column), in order to provide a quick estimation of the constraints whose improvement are likely to most benefit the entire product system. The ('N') column sums the negative interactions in order to provide a view of the constraints most likely to have a negative impact on the rest of the system, and are therefore the trickiest to address. 'T' is a binary sum of the interactions in order to show a general measure of connectivity—the most central constraints. At a glance the constraints with the highest connectivity score are those that are the most integrated within the structure of the constraint space for a particular design problem.

	S	W	Δ	P	N	T	A	B	C	D	E	F	G	H
A	1	3	1	0	-7	2	A			-3			-4	
B	2	4	2	10	-1	4		B	4			-1	2	4
C	1	2	3	8	-3	3		4	C		4		-3	
D	1	1	1	4	-3	2	-3			D				4
E	1,2	1	1	4	-4	2			4		E		-4	
F	3	2	1	0	-1	1		-1				F		
G	1	3	4	2	-12	5	-4	2	-3		-4		G	-1
H	3	1	0	8	-1	3		4		4			-1	H

Figure 6.24: Constraint 'B' has the most positive interactions, while constraint 'G' has the most trade-offs. Constraint 'G' is also the most highly connected constraint.

By summing all of the positive values in one column and all of the negative values in another, the CCMT provides a more representative picture of the constraint. Doing so can provide a quick view of the constraints that are most likely to cause difficulties and those most likely to be leverage points. If a constraint is characterized by many high-value negative interactions (lots of trade-offs), it is more likely to be problematic within the design process; changes made to improve this constraint are likely to have negative effects on other parts of the system, and vice versa. Conversely, a constraint which has a large number of high-value positive interactions may represent a highly influential point in the system, and changes made to improve this constraint may improve performance along a number of other dimensions. Accordingly, it may be beneficial to invest additional time, resources, or effort with respect to exploring this aspect of the design.

6.4.8 Building an Understanding

The CCMT encourages design teams to negotiate an understanding of the problem by forcing them to articulate what they feel is relevant, and to explore how those constraints interact. But the CCMT is not intended to be a 'once and for all' statement about the nature of a design problem. Instead, the goal of the CCMT is to assist design teams in collaboratively constructing their shared understanding of the design space. That understanding will grow and shift over the course of a design project as designers learn about the problem and the solution [64]; and the CCMT is designed to grow as well. It is not intended to be completed in one sitting,

and should instead grow and change as new information about constraints and relationships comes to light, in order to reflect the team's current understanding of the problem.

When exploring the initial formulation of the design problem, it is beneficial to prioritize the tracking of the more generally applicable constraints. These constraints can help the design team develop a sense of context, as they are likely to be relevant regardless of the eventually determined design direction. Many socio-cultural constraints, for instance, are likely to be relevant regardless of the chosen design direction, as they represent the knowledge and expectations that underlie a group's desires and behaviors. As the process continues and designers begin to solidify a direction and concept, new constraints can be added with regard to the more dependent constraints. Adding constraints too early in the design process, on the other hand, can be problematic as they cannot be recognized adequately until the problem and solution have been more fully formed. Prematurely including concept-dependent constraints in the CCMT can preclude potential design directions, because adding unnecessary constraints can predispose a design team to certain outcomes, and block others entirely [169]. This is one of the limitations of the tool, as it is possible to over specify the constraints too early in the process. But if designers are able to populate the CCMT in step with their growing understanding, it can function at increasing levels of fidelity throughout the process—acting as a way to build an authentic understanding of a complex system.

When taken as a whole, the concurrent constraint management tool provides a highly visual framework for understanding a design space. It is intended to help designers to better recognize and manage the full complement of constraints that are relevant with respect to a particular design activity. Across its various parts, the CCMT is intended to help design organizations to shift perspectives, anticipate change, and increase the understanding of constraint interactions, potentially harmful trade-offs, and valuable leverage points. Additionally, it may hold significant benefits for collaboration among designers and across organizational units, as well as the potential to improve the quality of those interactions. These potential advantages are only possible as a result of leveraging knowledge gained from the exploration of complex systems, hierarchy, polycentric control, and product architecture.

6.5 Diverging from Existing Tools

The concurrent constraint management tool is in many ways inspired by, and similar to, each of the tools described in *Section 6.2*. Many of the similarities across these tools are due to their desire to bring clarity and ease of analysis to systems that are, because of their complex nature, inherently difficult to model. As discussed, the performance and behavior of complex systems is driven by the interaction of the system components more so than the components themselves. Accordingly, each of these tools is primarily concerned with relationships more than the product's (or system's) parts in isolation. The HOQ charts relationships between consumer attributes and engineering characteristics, as well as between the engineering characteristics themselves. Product–based DSMs focus on the relationships between components in an $N \times N$ square matrix, and the CCMT does the same for the constraints which characterize a given design context. The importance of interactions, over individual parts, is precisely the reason that all of these tools share an underlying matrix structure, as a matrix is focused on the relationships that exist at the intersection of two or more items.

Each of the tools also pertain to relationships that can be difficult, if not impossible, to quantify accurately. This can be seen in the way in which each of the tools is typically populated: the HOQ relies on symbolic assessments, while both the DSM and the CCMT represent qualitative data with numerical scores. In the case of numerical representations, this generally allows for easier assessment, data entry, and more graduated scales—in many instances, these numbers can easily be replaced with colors or symbols that represent the same underlying qualitative assessment [271]. With all of the tools, qualitative assessments that are accurate with respect to the underlying relationships are more valuable than forced quantitative metrics which may or may not accurately depict the system being modeled. Within the space defined by these often imprecise relationships, however, all three tools have the benefit of directing attention to critical *interactions*. In encouraging designers to explore the relationships that invariably exist among given system components, designers are more likely to recognize the important relationships which drive system behavior or present significant challenges within the design process. Once these high-value interactions have been identified, it is possible to direct efforts, supply extra attention, and more closely monitor these important relationships with an eye towards their impact on the overall quality and fitness of the design.

With regard to actual application, the process of creating (or populating) these tools often holds great value—in some cases the process of creation may be just as valuable as any output or 'final product' [271]. The final HOQ, DSM, or CCMT can offer a great deal of insight with regard to the system's structure or critical factors, but generating and populating these tools can force designers and design teams to understand the systems they are designing in a much deeper way [271], [277]. Doing so can also lead to recognition of important factors or relationships which might have otherwise gone unnoticed.

Further, if leveraged appropriately, each of these tools can strengthen communication within an organization or design team. They can encourage communication across groups that traditionally have had limited interaction, and strengthen communication between groups and individuals more comfortable with one another. Despite the many characteristics the CCMT shares with HOQ and DSM analysis, the CCMT possesses a few fundamental differences and offers a number of advantages over those tools. These distinctions allow the CCMT to be deployed in situations, and for purposes, that are not possible with either HOQ or DSM analysis.

As constraints are more closely tied to the realities of the actual artifact system, the CCMT is geared to facilitate *exploration and understanding*. This is the fundamental difference between the CCMT and other matrix based tools. Rather than merely assessing known solutions or organizing known parts, the highly-flexible constraints of the CCMT enables it to be used to generate ideas and explore innovative directions.

DSM analysis served as a large inspiration for the creation of the CCMT, and the structure of the CCMT, in particular, is largely based upon that of a DSM. As a result, it is possible to view the CCMT as an extension of DSM modeling, although there are a number of fundamental differences. In their current state, DSMs help designers to identify proper architectures for an established set of components, but the focus is on the relationships between *previously established* parts of an artifact. DSMs do not help to determine what those parts should be, or what they should do. Given this, traditional DSMs offer little help to designers questioning whether these are the right components at all, or whether these components will help to perform functions relevant to an artifact's stakeholders.

Much like a DSM, the CCMT intends to capture relevant interactions and trade-offs that exist between components. The act of populating either tool will almost certainly provide designers with a deeper sense of the structure of a problem or system. In a component-based DSM, this 'structure' is the physical structure of the artifact, but because the CMMT's interaction matrix is populated with constraints that exist both internally and externally to the artifact, the illuminated structure is quite different. The CCMT provides insight into the underlying structure of the design problem. As the CCMT focuses on *constraints* rather than *components* and extends the system boundary beyond the artifact to include many extrinsic factors as well, the ability of the CCMT to suggest "optimal" configurations is further reduced. However, this further increases the importance of the CCMT's role in identifying important relationships and suggesting alternative perspectives. Accordingly, one of the primary goals of the CCMT is to extend the benefits and analysis of DSM to include exploration, innovation, and anticipation that can only come when we begin to look outside of the artifact, and focus on its connections with the ongoing field of activity.

While HOQ analysis somewhat broadens this perspective (with the inclusion of customer attributes), like the DSM it is geared towards the assessment and execution of an already established design solution. This is because when designers select customer attributes, they are essentially establishing the design's functions and capabilities—there is nothing to help designers explore what these customer attributes should be. From this point forward, the HOQ is all about the execution of the design, and how to achieve this given set of user attributes. Once again, there is nothing in the HOQ that is intended to actively encourage exploration of the design space. Additionally, constraints embodied within all five of the CCMT's constraint categories are more closely tied to the actual application of the artifact, which encourages designers to take perspectives ranging throughout the contexts of design, manufacturing, use, sales, etc. This is also one of its largest sources of additional value, as it allows designers to understand the full constraint space in ways not possible with either HOQ or DSM.

Focused on relationships and trade-offs, the roof is the part of the house of quality that is most relevant to the understanding of large complex artifact systems, and accordingly the most similar to the final design of the CCMT. The CCMT builds on the basic concept embodied in the roof of the HOQ: by extending beyond measurable engineering characteristics, and focusing instead on the underlying drivers of the design process. This difference means that the CCMT is

more suitable for exploring what to design, rather than just how to execute it. Within a problem, or design space, there are constraints and opportunities that interact, and must be navigated and balanced in order to identify a design direction, constraint prioritization, and an appropriate framing of the problem. As the result of many external factors, the conceptual design phase is much harder to optimize than the detailed design of known components, for which DSM is traditionally used. That, however, does not reduce the importance of the conceptual design phase, and there is a great deal of support for the idea that the identification of fit problem formulation is tantamount to designing innovative products [55], [62], [64], [169].

Rather than merely being useful in the detailed design phase, the exploratory nature of the CCMT allows it to be potentially useful across a broader range of design activities then either DSM or HOQ—from conceptualization to the assessment of a final design solution. If used appropriately, the CCMT can provide a platform for understanding and exploration across a variety of design activities. During the conceptual design phase, it can encourage a holistic exploration of the constraint space and a negotiation of a shared perspective within a team. It accomplishes this by forcing designers to build a shared model of the design problem, and allowing them to shift between alternative focuses, constraint prioritizations, and possible design directions. The CCMT can assist designers in identifying what the design *will be*, and what role it will play for each stakeholder. As designers attempt to execute a particular design concept, the tool encourages a focus on the underlying system structure, and helps designers to recognize and manage the trade-offs that exist within the constraint space. Thus the CCMT assists designers to better anticipate how changes intended to benefit one area of the design may affect other design goals and constraints. The CCMT is also potentially useful after the artifact's introduction into the field of activity. It has the potential to help structure research and direct the exploration of future opportunities, acting to facilitate the management of products in the face of a dynamic constraint space. This may help an organization to build upon what they have previously learned, and feed that information forward into future design processes.

Looking to Alexander's design method, all of the discussed tools share a focus on the relationships that exist between elements, but the CCMT and Alexander's method both share a broader focus than either HOQ or DSM. The inclusive nature of the set of constraints which drives Alexander's method—it is not limited to individual components or any single portion of the design process—represents the greatest similarity to the CCMT. It is this focus on a wider

range of factors that allows both Alexander's method and the CCMT to encapsulate the realities of a design's performance in a field of activity. Both focus on understanding the structure of the larger more complete design space, which exists at the intersection of the artifact and its context.

A fundamental difference, however, is that Alexander's method is very much structured to deliver an *appropriate* structural decomposition of the set of constraints. As illustrated, however, finding a 'correct' perspective or decomposition is exceedingly difficult, if not impossible, within complex artifact systems. Contra Alexander's method, the CCMT prioritizes shifting between multiple perspectives on the system, learning from each and building a more complete understanding in the process.

In many aspects of its design, the CCMT is intended to be both more flexible and more immediately applicable than Alexander's method. For Alexander's method to perform adequately, one must first prepare an exhaustive list of functional constraints that are defined "…to be as small in scope and hence as specific and detailed and numerous as possible" [4]. In *Notes on the Synthesis of Form*, his example consists of 141 constraints that are enumerated before his method can be used. His method has proven to be rigid, difficult to understand, and similarly difficult to apply within an actual design setting. The CCMT is designed to be more organic and easily applicable to real-world design processes. It does not rely on formal algorithms in order to define a single correct breakdown of a design problem. Instead, it is intended to aid learning about the relevant constraints and the underlying problem structure in order to facilitate the exploration of alternative directions and problem framings.

The CCMT exists to help designers grow their knowledge of a design problem and its context, and can be naturally constructed as designers proceed through the design process. Because the CCMT does not rely on algorithms, all of the constraints do not have to be populated prior to its use; constraints can be added and changed in accordance with the design team's changing understanding of the problem. While a CCMT may end up with 141 constraints, all of them do not need to be listed before the tool can be used: in fact, much of its value comes from building an understanding, and growing an organic matrix over time.

With the passage of time, Alexander himself would eventually refute his own, and other similar, solution–focused design methods. Because these methods were intended to actually drive the design process, they encountered a number of problems such as: the probability of

missing relevant constraints, the inability to deal with relative weights among constraints, the inability to deal with high level interactions, and the reality that design components may interact in ways that requirements do not capture [4]. Additionally, these rigid design methods struggled to adapt to future and changing constraints—something that is crucial within complex design processes. The fact that all assumptions and requirements are not knowable prior to beginning a design also posed great problems for these design methods [286]. The assumption that these algorithmic methods could be used to solve design problems flew in the face of the reality of design as a learning process—in which each step has value for shaping the design process and the designer's understanding [55], [64], [169]. The CCMT has been designed with the understanding that all of these complications are the inevitable realities of attempting to understand complex artifact systems. Rather than rendering the CCMT incorrect or invaluable, these are recognized factors that the tool helps designers to understand and manage.

The CCMT is intended to be a clear and deep exploration of a specific design problem, and to be valuable to designers as a framework for understanding. It is primarily a descriptive tool, rather than a prescriptive one. It allows designers to make their own decisions and explore in their own way, facilitating a better understanding of the problem's structure through the CCMT's creation. The CCMT does not rely on any specific algorithms in order to suggest any particular decomposition or system clustering, but this does not reduce its value within the design process. Instead, it is the construction of the CCMT matrix and its visual presentation that holds value. Like product DSM, the visual nature of the CCMT allows designers to quickly and intuitively assess the design space, and to consider alternative framings of the design problem.

In fact, leading DSM researchers Eppinger and Browning recognize the tremendous value of creation, even apart from detailed optimization techniques: "In almost every DSM application, we have found that the visual display of DSM can be used to tremendous benefit—perhaps even more powerfully than the analytical tools that support DSM" [271]. The CCMT eschews traditional analytical tools in order to hone its ability to bring clarity to complex artifact systems. Populating the five constraint categories and exploring the constraint interactions holds considerable value in and of itself, and facilitates learning through the construction of the matrix. This process, in addition to the visual presentation of constraint information, helps designers in identifying solutions that are better positioned with respect to the underlying constraint space, as

"the most successful designs are not those that try to fully model the domain in which they operate, but those that are 'in alignment' with the fundamental structure of that domain" [17].

Additionally, the CCMT is intended to be a collaborative tool, with many of its largest advantages only emerging when used across designers, teams, and organizational structures. Used by a single individual, the tool will be unable to capture all of the relevant constraints, and is likely to miss a high percentage of the relevant interactions within the constraint space. Shared construction of the tool, particularly if it occurs across disciplines, can lead to a picture of the design problem that is more closely aligned with the realities of product development and use. Trans-disciplinary construction may also have the benefit of helping to develop a shared vision of the design problem—allowing designers and relevant stakeholders to negotiate a common understanding of what is relevant and important. It may also serve to create greater buy-in, and establish a framework for shared exploration and envisioning, by encouraging designers to collaboratively explore the design space and frame the problem in new ways. As the design process plays out over time, it also has the potential to act as a centralized tool to help manage organizational understanding, and help designers to assimilate knowledge from different points throughout a design organization.

In conclusion, the concurrent constraint management tool's distinctiveness with regard to both the HOQ and the DSM is primarily tied to its focus on design constraints, and its ability to encourage exploration and understanding for factors external to the artifact. By focusing on constraints instead of components or particular solutions, the CCMT provides designers a way to stay grounded in the activities, desires, and goals that exist at the level at which the product becomes meaningful to users. Its uniqueness from Alexander's method is tied more to its specific implementation—in that it is an actual functioning tool, and in the particulars of its operation. Its underlying purpose is not as an algorithmic tool for decomposition, but as an aid for designers to construct their own understanding of the full constraint space. The value of collaboratively building this model cannot be overstated, as this activity facilitates group learning and exploration that can be leveraged within each designer's own processes and solution exploration. Accordingly, it is more geared toward exploration and understanding than it is to the actual execution of one particular design. By focusing on these factors, the CCMT acts as a concise visual representation of a complex artifact system that creates value across a larger swath of the design process.

6.6 Considerations and Difficulties in Applying the CCMT

The Concurrent Constraint Management Tool offers a number of benefits with respect to managing design activity in complex artifact systems. It attempts to remain authentic to the realities of real-world design processes by representing the underlying constraint structure in a visually concise way, and by allowing practitioners to explore within that structure. There are, however, still a number of considerations and difficulties in applying the tool within the design process. Many of these issues have been recognized as a result of the tool's implementation in the two studies discussed in *Chapter 7*.

- **Data Challenges** Creation of the CCMT embodies potentially heavy data requirements with regard to acquisition, aggregation, and consistency. Data and information that is not readily available, easily collected, or quickly assimilated is frequently required in order for the CCMT to accurately reflect the actual design space. This can make the construction of the tool difficult, particularly in the initial stages of the process when the information about the design space is just beginning to emerge.

- **Reliance on multiple perspectives** Individuals associated with specific parts of the design, or constraint space, are more acutely aware of the constraints, interactions, and trajectories within their part of the system. This puts an emphasis on collaboration in order to overcome local data—a potential strength of the tool. But if collaboration does not occur, this information can be difficult to aggregate, categorize, or even comprehend by a single individual or team. This can potentially lead to the creation of an unrepresentative CCMT, which may inspire confidence or spur action, despite holding little actual value.

- **Psychologist's fallacy** In populating the matrix, it is important to avoid hindsight bias and the psychologist's fallacy (assuming the current understanding of the system is the correct understanding of the system). There is a natural tendency for designers to want to populate the matrix with constraints that are perceived as relevant based upon a particular envisioned future, direction, or solution. Doing so, however, limits the effectiveness of the

tool. At least initially, designers should make every effort to explore the constraint space independently of the artifact as currently envisioned.

- **Limited, non-holistic, use** As a result of its rigorous and highly specified structure, use of the CCMT may be met with hesitancy in some design settings, leading to incomplete use of the tool. This may result in the tool being used to justify design directions and decisions, rather than helping to search for them—predisposing designers to the psychologist's fallacy. The CCMT is intended to be used throughout the design process as an aid to understanding, exploration, anticipation, and idea generation, but its effectiveness is limited if it is included only in an *ex post facto* way.

- **Ambiguous constraint definitions** Identifying and defining constraints in a way that is representative of the actual design space and context is important. Over-simplified, over-generalized, and stereotypical representations of constraints offer little real value in explaining or understanding the underlying structure of a system. In order to provide real value, constraints must be defined at a level of detail which accurately reflects the realities of practice.

- **Qualitative ratings** Much of the strength of the CCMT lies in its ability to encourage designers to consider the relationships among a set of often-qualitative factors. At the same time, these qualitative relationships can often feel overly arbitrary. In the worst case scenario, this can lead to an overall reduction in perceived value, or a distrust of the tool. Additionally, if the values are populated by individuals with a differing sense of scale (what is a '3' to one rater, may be a '2' to another) these qualitative ratings can cause difficulties. Accordingly, establishing a clear rating scale is key.

- **Constructing the matrix at the correct scale** While there is no maximum size for a CCMT, there may be limitations based upon practical application by designers, managers, and organizations. Alternatively, if the CCMT is too small, it is unlikely to capture an adequate range of constraints and interactions—limiting the usefulness of the tool.

- **Establishment of constraints and interactions at the appropriate time**
  The structure of the tool can, in some ways, encourage designers to populate the tool in an "eager" manner, by giving the impression that the entire matrix needs to be populated in a

single pass. Doing so can lead designers to over specify the constraint space by imposing constraints before they are necessary. This can manifest as a deterministic application of the CCMT in which the chosen constraints, rather than the problem itself, direct the design solution. For instance, listing certain physical constraints (e.g. the device's handle must support 15 lbs.) prior to determining a design direction can cause designers to prematurely narrow and preclude alternative directions (the previous constraint assumes a handle is necessary, and therefore hides alternative methods of carrying or supporting weight). Doing so can result in an over-specified view of the constraint space that limits, rather than encourages, exploration.

As a result, there is a need to populate the CCMT at a pace appropriate to the actual design activity. While this differs from process to process, socio-cultural constraints will typically apply regardless of the design direction, and can therefore be populated early in the process. On the other hand, populating many of the physical and technological constraints too early can actually bias designers toward specific solutions, and should therefore be postponed. Designers need to be cautious to populate the tool at a pace appropriate to their process, allowing it to grow in step with their understanding of the design problem and the solution. Within an educational setting, it may even be beneficial for instructors to direct the pace at which teams populate the matrix. Encouraging students to first focus on the more generally applicable socio-cultural constraints, prior to populating constraints more related to a specific design direction, would be one way to do this.

- **Limited visualization of data and relationships** Although the CCMT has been designed to present a complex set of data in a visually informative way, the matrix structure has its own set of limitations. Particularly, the matrix structure is not overly intuitive to those unfamiliar with matrix based tools, and individuals may find other network representations more accessible. This is particularly true if the tool is intended to be leveraged across multiple disciplines: while engineers will likely be comfortable with the structure, industrial designers, managers, manufacturing personnel, etc. may find the form a bit difficult to digest initially.

- **Non-intuitive usability and Excel difficulties** The nature of programming in Excel makes certain operations difficult and inconsistent. Dynamically highlighting cells, for

instance, required multiple operations, which lead to inconsistent and choppy performance (animation of the cells). Similarly, certain operations required that steps be carried out in a precise order in order to maintain the structure of the sheet. While the tool can add rows and columns, adding or removing multiple columns in succession, without manually entering a new constraint ID after each, would cause the program to incorrectly shift the pre-existing data. The program was also prone to crashing. But perhaps the biggest flaw is that the 'undo' action is unavailable within an Excel program—so saving often is a must.

6.7 Extending the CCMT

6.7.1 Continued Tool Development

Through the CCMT's application in an educational setting and detailed discussion of its features, a great deal has been learned about the capabilities and limitations of the CCMT. Accordingly, a number of design changes and extensions of the tool have been identified that can potentially improve its functionality and usefulness. Some of these changes are the result of failures in the tool, some are the result of technological constraints, and others are the result of learning that was initiated from the tool's introduction into its very own context of use. Some of these changes focus on usability and interaction design, while others extend the tool's core capabilities. The suggestions included here do not represent an exhaustive list, and each suggestion must be weighed with the broader goals and purposes of the tool prior to implementation. Across the board, each of these suggestions represent potential directions for the evolution of the concurrent constraint management tool.

1. **A stand-alone software package** Programming the current version of the CCMT in Microsoft Excel allowed the author to take advantage of the huge library of functions and capabilities included natively within the program. At the same time, developing the tool in Excel imposed limitations on the design. By developing the next version of the CCMT as a stand-alone piece of software, the tool can potentially be pushed forward in order to provide greater capabilities and functionality based upon research results and feedback from both academia and industry. Developing a new program would allow the tool to escape the limitations of Excel, but would sacrifice many of its benefits, namely,

easy distribution and built–in familiarity. This change, however, would likely be necessary in order to achieve a number of the changes suggested in this section.

2. **A dynamically sortable CCMT** Currently the CCMT is not sortable based upon any of the data within the matrix. There is potential value in being able to sort the matrix based upon criteria such as weight, rate of change, negative interaction score, etc. As the matrix is broken up into individual constraint categories, it would be valuable to sort globally as well as within any single category. Particularly for design problems containing a large number of constraints, this change would allow designers to more easily focus on the most relevant constraints, and ensure that interacting constraints do not adversely affect their resolution.

3. **Flexible constraint breakdowns** The CCMT is currently divided into the five primary constraint categories. While these categories provide an appropriate decomposition, there are other possible ways to break down the set which may be more applicable for a given design process. To reflect this, the CCMT should allow users to add and remove constraint categories freely. As an obvious example, if a user wants to add an 'aesthetics' constraint category in addition to the five standard categories, they should be able to do so. At the same time, if a user does not want to use any of the five standard categories and instead wants to define their own, the CCMT should allow that as well. This change would enable structural representations more in line with a particular design activity to emerge. If the tool were to be used for a software design process, the most appropriate constraint breakdown might look quite different from what is appropriate for physical artifacts. In this way, the tool itself provides the required capabilities, and users can bring the CCMT into a closer fit with their current needs.

4. **Nesting subcategories** The ability to divide a constraint category into a number of constraint subcategories would allow the CCMT to better reflect and manage the hierarchy and near-decomposability of a constraint space. By allowing users to group constraints into nested subcategories, the CCMT could be organized to facilitate deeper understanding and provide greater focus to a set of constraints. The category of usage constraints, for instance, could be broken down into physical and cognitive ergonomics, with physical ergonomics containing constraints relevant to physical interaction and fit, and cognitive ergonomics containing constraints relevant to interaction design, skill

acquisition, etc. Attempting to populate or focus on the whole set of constraints relevant to a design problem can be overwhelming, but nested sub-categories of constraints would provide finer resolution and thus greater accessibility. Implementation in this fashion would allow users to expand and collapse parts of the matrix as needed. This structure would allow users the ability to zoom in and out within the set of constraints, exploring different hierarchical levels and breakdowns.

5. **Selective focus** Allowing designers to show and hide constraints based upon specific criteria would help to better direct attention within the larger constraint space, thus allowing designers to avoid overwhelming amounts of data. Constraints could be hidden based upon nested sub-categories, as well as a number of other criteria (weight, expected rate of change, connectivity, etc.). It would be possible to show/hide constraints based upon stakeholders (allowing users to more quickly shift between perspectives), relative importance (directing attention to the constraints with the highest priority), or expected rate of change (increasing the visibility of the most uncertain aspects of a design). It would also be possible to dynamically hide portions of the matrix based upon the interaction threshold value, showing only those constraints which have the strongest interactions. If users wished to see the most significant trade-offs, for instance, it would be possible to show only those constraints which have interactions valued at '- 4'. By hiding various parts of the larger constraint set, however, it is possible that users would miss important interactions and trade-offs that exist within the larger space (by hiding one of the interacting constraints). In order to avoid this, it would be necessary for the CCMT to be able to alert users to broken, or hidden, high-value interactions.

6. **Tracking performance** By adding a *performance column* (*Figure 6.25*, column "*P*"), it would be possible to estimate the current state of a design concept with respect to each constraint. Used within the design process, this column could help design organizations to recognize the constraints which are satisfactorily addressed, and those that still require focus and design efforts. This additional column could act as a checklist of sorts, encouraging designers to identify and address what Alexander called 'misfits' within the design [4]—by highlighting the constraints that still need to be addressed within the design. This performance column could be populated with numerical estimates of completion, or colors: red representing unsatisfactorily addressed, etc. This column

would serve as a representation of where action still needs to be taken with the constraint space, but these assessments would be likely to change throughout the design process. As designers proceed through the process and make changes intended to address a particular constraint, they can refer to the interaction matrix in order to get a sense of how these changes are likely to affect other parts of the design—giving them foresight into future directions and possible problems. Used in this way, it is possible that designers may anticipate potentially negative implications that would not have been otherwise recognized until after the occurrence of the negative consequence.

This aspect of the CCMT may also hold considerable value if the tool is used across multiple development cycles. Rather than populating the performance column with the designer's perceptions about an unfinished design, this column could alternatively be populated based upon the artifact's actual performance. Thus the tool could act as a guide for post-release product evaluation and research, performing a similar function to the benchmarking matrix in the House of Quality.

	S	W	Δ	P	N	T	P	A	B	C	D	E	F	G	H
A	1	3	1	0	-7	2		A			-3			-4	
B	2	4	2	10	-1	4			B	4			-1	2	4
C	1	2	3	8	-3	3			4	C		4		-3	
D	1	1	1	4	-3	2		-3			D				4
E	1,2	1	1	4	-4	2				4		E		-4	
F	3	2	1	0	-1	1			-1				F		
G	1	3	4	2	-12	5		-4	2	-3		-4		G	-1
H	3	1	0	8	-1	3			4		4			-1	H

Figure 6.25: Potential negative impacts of addressing the unsatisfactorily addressed constraint 'G'.

7. **Linking information to the CCMT** Because the CCMT is intended to act as a repository of information from throughout the system, it has distinct advantages if it is populated collaboratively. One way that this functionality can be extended is by allowing individuals throughout an organization to link information to the CCMT itself. Descriptions, files, web-links, research results, data, etc. could all be conceivably linked to the CCMT. This offers a number of potential capabilities and advantages: (1) it could act as a central information resource for designers. (2) It could enable individuals

throughout the design organization to learn and explore the full constraint space. Imagine clicking on a particular usage constraint in order to explore the actual research data and videos, or clicking on a physical constraint only to be provided with detailed engineering drawings. (3) It could act as a polycentric source of information. As the amount of information relevant to any complex design process is vast, populating the CCMT with every relevant link would be an almost impossible task for any one individual. Accordingly, the CCMT's links could be populated by those individuals and groups most closely associated with individual constraints. While no one would be expected to view every single linked file or document, their presence would allow individuals associated with the process to explore as deeply as they desired.

8. **Tracking change** The CCMT is intended for use as a dynamic tool, implemented and changed throughout the design process. As such, it may be beneficial to allow design organizations to track the way in which the CCMT has changed over the course of one, or multiple, projects. Ideally, this would take the form of a 'date-slider' within the CCMT that would allow the matrix to be viewed as it existed at any point in time. This would effectively allow designers to step through the history of their understanding of the design problem. It seems probable that viewing the evolution of the constraint space over time would help designers to better anticipate future change.

9. **Differentiating constraints based upon certainty** Constraints whose relationships are explicitly known (as a result of observation, testing, experience, etc.) are currently tracked in the same manner as those relationships that are estimated or perceived. This can lead to situations in which the visibility of known interactions is reduced. As a result, it would be beneficial to include a way to differentiate relationships based upon the certainty of the interaction. This could be accomplished in a number of ways, including adding a certainty score, color coding relationships, etc. A similar implementation was included in a DSM used by the Adaptable Futures research group at Loughborough University intended to help architect design schools that will accommodate the changing demands of users. This DSM color coded the relationships within the matrix to differentiate between dependencies that were 'explicit,' 'inferred,' and 'perceived' [271], [287].

6.7.2 Implementing DSM Clustering Algorithms

There is clear potential to combine the CCMT with more traditional DSM clustering algorithms in order to suggest product architectures based upon the rate of constraint change (Δ). Rather than basing architectures solely upon the functional interactions of known components, this method could suggest new architectures based upon the speed at which constraints change in the world, allowing for products to be better equipped to evolve in step with the constraint environment in which they are embedded. Novel architectures represent potential paths to innovative design solutions [257], and as discussed in *Chapter 5* grouping constraints and components that are changing at similar speeds is one way in which these new architectures might be envisioned. These architectures would be exploratory in nature, and intended to help an organization design architectures that would adapt more quickly in the face of a changing constraint space. In order to accomplish this, the CCMT would have to be coupled with a more traditional component-based DSM—as constraints exist across components, and product architectures are built upon components, not constraints.

6.7.3 Continued Learning and Knowledge Management

Another potential way that it may be possible to extend the functionality of the concurrent constraint management tool is by tailoring it for use as a long-term knowledge management tool. The CCMT could be positioned to grow and evolve in conjunction with designers' understanding over the course of one, or multiple, design cycles. This includes managing constraints that arise during the design project, as well as constraints that are recognized after an artifact has been designed and released into the market. Doing so may help organizations to better manage iterative design cycles, product platforms, and product families, by establishing a knowledge base that grows and changes as the organization learns.

For new projects, the CCMT must be populated from scratch, but subsequent design processes for generational or related designs can potentially leverage previous efforts and act as a way to capture knowledge gained after the product's release. The first time the CCMT is populated, many of the constraints and interactions will be hypotheses. But after a product's

release, these constraints and interactions can be amended based upon numerical and experiential data, allowing the constraint matrix to more accurately capture the constraints and trade-offs as they actually exist within the system. Doing so has the potential to help design organizations avoid "relearning" the same information with each new project, and act as a framework for post-release product research.

The point of an artifact's release has huge significance. It is the mesh point between the design process and the constraint space. It is the point at which the designers' hypotheses about the product, use, and the constraint space are all put to the test. Therefore, studying how products are used and adapted after an artifact's introduction may hold great value—allowing designers to form a better picture of the constraint space through a continued focus on the CCMT. How well does a product function in a given context? What are the factors ultimately responsible for the success or failure of a product? What are the positive and negative effects of the problem setting, constraint focus, and design decisions? What were the unrecognized constraints? The notion of using the CCMT to structure post-release product research by directing attention to the aspects of a design which are of the most importance, or changing the most rapidly, seems to open a potential avenues for future research.

In many ways, this idea is similar to the concept of Post Occupancy Evaluation found in architecture, in which buildings are evaluated along a number of dimensions after they are constructed and occupied for a period of time. By studying buildings after they are "lived in," architects hope to evaluate the performance of a building and search for inspiration for future design projects. According to the authors of *Post Occupancy Evaluation*, studying a building after its introduction helps architects to avoid the traps of incremental improvement. Stating that, "so much is built so quickly and so much can change and innovation occur that problems… can be replicated many times before they are discovered" [288].

Similarly, by investigating a design solution's fit with respect to the set of constraints established in the CCMT, design organizations may be able to recognize problems before they are replicated in future products. While this is easiest to see with respect to problems, the same is true for the identification of opportunities, with opportunities for new markets and innovations persisting unnoticed. By using the CCMT to further the understanding of the constraint space after a design has been introduced, new opportunities may be recognized more quickly.

At the same time, there are still a number of challenges that the CCMT must overcome if it is to be used in this way. Primarily, designers must recognize that one reason designers rarely revisit their designs is because of acute pressures from specific market constraints—most frequently, time and money. Asking designers to maintain the CCMT after an artifact's release may have value, but realistically this activity may be squeezed out as the result of pressure to move on to the next project. But tracking change in the constraint space, and developing artifacts that remain in step with that change, are the responsibilities of designers. The CCMT may therefore present an opportunity to improve the efficiency of that process, and help to justify the expenditure of resources by increasing the visibility of opportunities for innovation. Deployed in this way, the CCMT may help to facilitate useful, economical, timely, and beneficial evaluations of products and or a constraint space. This, in turn, may help to maintain the value of current designs, improve future design variants, and open new design possibilities and directions.

6.8 Conclusion

Much has been learned based upon the design and implementation (*Chapter 7*) of the CCMT. In its current state, the CCMT represents an original direction that holds great promise for helping designers to manage the effects of complexity on the design process. The CCMT is built to reflect this complexity, and to simultaneously increase its tractability. Like any good design, the creation of the CCMT addresses existing struggles and opens new avenues for exploration. What follows are ten final thoughts on the concurrent constraint management tool:

1. *Similar to DSM tools, a little modeling can go a long way* [271]. Considerable insights can emerge from relatively small amounts of modeling effort, and the CCMT can provide deep insight and understanding without ever running an optimization algorithm.
2. *The CCMT is intended to aid designers, it does not replace them.* The CCMT is not designed to suggest design solutions. Quality design outcomes are still reliant on the creativity and skill of designers and engineers; the CCMT simply facilitates understanding and exploration which can lead to key ideas and innovative directions.

3. The *concise visual representation* of the CCMT allows designers to more quickly understand the underlying structure of the artifact system. By highlighting the relationships of consequence, it is possible for designers to identify leverage points and anticipate potential breakdowns.
4. The CCMT *illuminates second level interactions and trade-offs*. While first-level relationships are often easy to identify, second level-interactions are much more difficult to anticipate. Because of this, they are frequently the cause of emergent system behaviors and breakdowns. Better recognition of these relationships, can lead to better anticipation and more robust designs.
5. The *CCMT's strength is in the constraints*. A traditional DSM's focus on components makes it useful only after the components are defined. The CCMT's focus on constraints encourages understanding and exploration of the design space—leading to new problem formulations and design directions.
6. The *CCMT is about perspective*. Creation and use of the CCMT encourages designers to recognize and understand the many stakeholders within an artifact system. It also provides a way for designers to shift amongst these perspectives in order to search for inspiration and identify potential complications.
7. Even without clustering algorithms, the CCMT can suggest architectures based upon the *speed of change* in the environment. Identifying architectures based upon the rate at which the underlying constraints are changing, rather than simple component interactions, can lead to alternative and innovative product architectures.
8. The CCMT offers *usefulness across the entire design process*. During the initial phases of the design process, it facilitates understanding and helps identify a direction. During the execution of a design, it can help to track and anticipate changes, as well as suggest innovative architectures. Upon completion, the CCMT can help manage designs in the face of a dynamic environment.
9. The CCMT transcends theory and is *focused on design practice*. It strives to be useful and authentic to the realities of real-world design processes, by providing clarity to the underlying constraint structure. The CCMT does not purport to eliminate complexity; it helps designers to navigate it.

10. The *CCMT is a flexible model*. Because the CCMT is not tied to a single algorithm or program, it can be easily modified to fit the needs of many unique design contexts.

Constraints are significant in their relationship to the design as well as other constraints [111]. Accordingly, the CCMT helps to more accurately reflect the interactions present within a complex artifact system. In this way, the complexity of the constraint structure reflects the complexity of the world, while it making it more accessible. The CCMT offers a number of benefits with respect to managing design activity in complex artifact systems fraught with trade-offs, but its application is not a panacea intended to address every problem and complication. The CCMT does not make design any less of a messy activity, nor does it ensure successful solutions. It is also not a prescriptive model, intended to output "correct" system breakdowns or solutions. Instead, the CCMT is intended to act as a framework to facilitate understanding and exploration within a larger constraint space in a concise manner.

The CCMT was built in order to help make transparent the structure of a complex artifact system, and the constraints which underlie them. Many of the more difficult issues inherent within complex design processes are addressed: structure, perspective, trade-offs, focus, prioritization, cascading effects, emergent behavior, and change. The approach described here is intended to be accessible enough to be deployed in practice, while still providing benefits which are unavailable in other similar approaches. The CCMT offers a visual and concise representation of the artifact system which can help to encourage understanding, exploration, anticipation, and collaboration in a way that benefits ongoing design development processes.

In conclusion, the CCMT stands as a novel and potentially useful addition to the class of qualitative models currently characterized by tools like the Design Structure Matrix and the House of Quality. The CCMT is not a perfect solution to the challenges posed by complex product design and development processes. It is a flawed tool. But given our understanding of complex systems, this is inescapable. Every perspective, every tool, every model is flawed. Our knowledge is flawed too, but none of these are reasons to ignore potentially useful tools. While there are certainly examples of designs that succeed without tools such as the CCMT, there are still more products which do not succeed. Those designs fail for a wide variety of reasons that

can be traced back to every constraint category—with failure frequently emerging from the complex interactions of the underlying constraints.

Accordingly, the CCMT exists in order to help designers balance constraints and better manage complexity, thus increasing the likelihood of developing successful design solutions. While the CCMT is not perfect, it still holds great value as a framework for design activity—encouraging deep exploration of the problem, and acting as a useful reality check for a design organization's knowledge, perspective, and direction. Designers' knowledge, perspective, and understanding are inherently imperfect with respect to a complex design problem; so too is the CCMT. But used together, each is more powerful than if leveraged separately. Combine that with the immense skill and creativity of designers, and it is possible to design artifacts that are better positioned to deal with complexity and change.

Chapter 7: Concurrent Constraint Management Tool: Application, Study, and Analysis

7.1 Introduction

In order to assess the value of the concurrent constraint management tool, it was deployed within an educational setting in a course focused on engineering product design. The tool was used by student teams as they attempted to identify and address real-world design challenges. The effectiveness of the CCMT was evaluated along a number of dimensions ranging from its effect on teamwork to the tool's ability to help generate design directions. While this study was geared primarily towards assessing the effects of the CCMT within the context of engineering design education, it is possible that similar results may be seen in the context of industrial design education, architectural education, and even actual design practice. In this way, the CCMT opens a number of potential avenues for future research. The duration of this section will serve to discuss the structure of the research study as executed, and its results.

7.1.1 Research Objectives

The purpose of this research was to determine the value of the CCMT both as an educational strategy and as a curricular tool in the context of an established engineering-design education setting. The basic hypothesis was that the CCMT would provide benefits to student understanding, learning, communication, and outcomes—through the development of a shared language, understanding, and set of tools. The matrix was intended to assist in the recognition, categorization, and management of design constraints within a design problem, as well as provide students with an understanding of the trade-offs and interactions that exist among those constraints. Through the construction of this matrix, the intent was that students would develop an understanding that better reflects the complexity of a real-world design problem, thus

allowing them to better balance the effects of constraints, user perspectives (stakeholders), and contexts within the design process.

Over the course of a six-week design process, teams of students, who voluntarily elected to participate, were divided into experimental and control groups. Control groups completed the real-world design process without using the CCMT, while Experimental groups were provided with the CCMT. Throughout the course of the process, students within the experimental population were instructed on the use of the tool, and were periodically asked to provide feedback about the impact of the tool on their project. This feedback was provided in the form of surveys and informal interactions with the researchers. The design project concluded with each group submitting a final design solution, which was then evaluated by a panel of experts representing a diverse set of design backgrounds and skills. This evaluation served to assess the impact of the constraint-based approach on the outcomes of the students' design processes. While not an absolute measure of solution quality—a result of the inherent subjectivity of design assessment—these expert opinions represent an effective and feasible method of solution evaluation. At its conclusion, the study assessed the impact of using the constraint framework and the CCMT in the context of engineering-design education.

7.1.2 Background

As has been demonstrated, the constraints on a design problem can be used to categorize the unique set of factors relevant to a design problem. By generating a structure through which the constraints on a design process can be enumerated, organized, and discussed, it is possible to more efficiently and effectively guide students through the exploration of this space. Additionally, this structure exposes the interactions and trade-offs that exist among these factors, and that are a frequent cause of unexpected and emergent breakdowns within the design process. By incorporating these constraints into an educational strategy, it is possible to construct a scaffold through which design educators can communicate, lead, and conduct classroom instruction about the design process to provide students with a deeper and higher-fidelity understanding of how, and why, designs succeed and fail within a field of activity.

As an instantiation of these ideas, the CCMT represents a novel research direction. The goal of this study was to assess the impacts of the CCMT as an educational strategy on both the

students' understanding of design, and on their execution of the design process, using primarily qualitative methods. While there are no studies that deal with this particular approach, or its impacts on design education, there are a number of studies that focus on the application and outcomes of other matrix-based design tools. The majority of these studies are not human subjects research, and instead focus on modeling the components and interactions of a designed system in an $N \times N$ matrix with respect to the static architecture of a product, the structure of teams within a design organization, or the temporal pacing and scheduling of the design process [141]. Accordingly, it is possible to look to these related examples for an indication of how best to assess and analyze our data, which has been to this point primarily qualitative. This is largely a result of the complexity and difficulty associated with evaluating real-word design processes and outcomes [289]. This study uses both qualitative and quantitative metrics in order to develop an understanding of the true value of the CCMT as an educational tool and strategy.

Because of the subjective nature of design, and design evaluations, there are inherent difficulties in accurately assessing the value of the tool. For instance, a skilled group may perform well in either the control or the experimental population, just as an unmotivated group may perform poorly in either population. Generally, it is possible that a single group's performance may be good or bad as a result of a large number of factors not directly correlated with the CCMT. For this reason, this study looked at a number of factors related to design education that go well beyond the "quality" of a final designed artifact. The impacts of the new educational strategy on understanding, communication, team-work, and learning are all critical parts of the study, and are in many ways more important within the context of design education.

While this study is geared specifically to engineering design education, there are a number of potential benefits to both educators and students across multiple branches of design and education. Students may gain a better understanding of the design process, produce higher quality design solutions, or better retain the learning in their future coursework and careers. Educators will potentially be provided with new strategies to instruct, discuss, and structure course work in order to better facilitate the students' learning experience. There is also a pedagogical benefit in that the CCMT may help researchers to better understand how engineering students understand and approach design problems cognitively. Additionally, if the CCMT is helpful with regard to increasing collaboration, improving anticipation of the effects of

design change, or developing more successful design outcomes there may be benefits within actual design practice as well.

7.1.3 Research Design

This study was conducted over two semesters at the Ohio State University in the course Mechanical Engineering 5682/Industrial and Systems Engineering 5560 during the 2012-2013 academic year. The authors of this study were jointly responsible for the lecture and laboratory instruction of this course, which has the title 'Fundamentals of Product Design Engineering.' As this course teaches both engineering design practice and engineering design methodology, this particular cohort of students represented an ideal population for this research study. Of the five laboratory sections of ME 5682/ISE 5560, three sections were randomly assigned as the part of the experimental population (which used the CCMT), while the remaining two sections acted as the control population (which did not use the CCMT). Within each section, design teams of three or four students were randomly assigned and asked to solve a self-selected real-world design problem.

For this project, the student teams were asked to identify a real-world design opportunity based upon extensive user research. Each team ultimately developed conceptual design prototypes that addressed their selected design problems. Teams were given a great deal of freedom in selecting their user group and the direction of their design process, and accordingly a great deal of the project work was conducted outside of the classroom. The student teams chose to focus on a wide range of users, ranging from fire fighters and EMTs to nurses and surgeons. After selecting a user group, students were tasked to conduct primary interviews with no fewer than two users, in order to identify design opportunities and assess the potential of a particular design context. Once these interviews were conducted and approved, students were responsible for conducting applied ethnographic studies with users in the actual activity context. These sessions of detailed observation and discussion were intended to help users to articulate their needs, goals, and desires, and to give the student teams a deeper understanding of the larger context in which both the user and the product exist.

After conducting several *in situ* observations, students were asked to explore the nature of the problem and begin generating candidate solutions. Students were responsible for

generating and sketching potential solutions to the problem, continuing to develop those ideas into a more fully considered design proposal over the course of multiple weeks. They then developed a rough prototype of the design, which was used to present their problem and proposed solution to their classmates and their users. These prototypes served four primary purposes: (1) to solidify a large number of ideas into a single concept; (2) to learn about the design problem and the proposed solution in ways not possible without an appropriate representation [55], [64]; (3) to obtain feedback and insight from the rest of the class; (4) and to obtain feedback and suggestions from the user, with the prototype acting as a tool to catalyze ideas and facilitate discussion.

Finally, students were asked to reflect on the findings and insights from the communication prototype and then develop a final design solution. These solutions were ultimately communicated through the construction of a final prototype. Final solutions were presented to the class in conjunction with a presentation intended to convey an understanding of the design challenge and the ultimate value of the proposed solution. These solutions were "final" in the sense that they were relatively complete design concepts that represented a culmination of the academic term, but they were not, in any way, production prototypes or fully functional solutions. In addition to the final prototype presentations, students were asked to produce a two-page product summary which outlined the product's design, features, and how the design addressed the unique needs of their chosen user. The assignments for each part of this project and the students' two-page design summaries can be seen in *Appendix E* and *Appendix F*, respectively.

With the basic project structure outlined, the control groups worked through the design project according to the procedures and educational strategies previously used to guide the project, while the experimental groups worked through the same design process with the addition of the CCMT. The groups were each responsible for the same work and deliverables—research results, ideation, intermediary prototypes, and final prototype—and the students' presence in either the control or experimental population had no impact on their grade for the course. The introduction of the matrix-based educational tool was the sole difference between the experimental and control groups, and throughout the duration of the experiment both populations participated in surveys documenting their process, experiences, and the perceived

value of the CCMT. In addition to this structured feedback, the researchers also collected informal data based upon participant observation and informal discussion.

At the conclusion of the design process, the student teams from both populations were required to submit a final design, representing their solution to the chosen design problem. A panel of experts representing a range of design disciplines and expertise then evaluated these design outcomes. Rather than evaluating the actual prototypes and presentations (something that was not feasible given the classroom setting and time requirements), the experts based their evaluations upon the two page design summaries in order to maintain consistency. If any member of a student group opted out of the study, the group's design outcomes were removed from the study and were not evaluated. These evaluations represent a variety of data, and include quantified ratings representing the overall quality of the design, the creativity of the solution, the solution's innovation potential, and the students' recognition of the full set of relevant factors—all captured using Likert items. This evaluation was also left open-ended with the intent of capturing any comments and evaluations not effectively encapsulated within the survey.

At the conclusion of the research study the data was aggregated and analyzed in order to assess the CCMT's impacts on understanding, learning, teamwork, communication, and design solutions. The data has been statistically and qualitatively analyzed in order to identify higher order patterns that provide insight into the usefulness, accessibility, and desirability of the CCMT, and is contrasted with the pre-existing educational strategy (represented by the control groups, which did not use the CCMT).

7.1.4 Study Population

The sample size and study participants were determined by the students enrolled in ME 5682/ISE 5560. The test population of ME 5682/ISE 5560 was comprised primarily of senior undergraduate and M.S. graduate engineering students from a diverse set of engineering disciplines, predominantly students in mechanical and industrial engineering majors, with a few students from electrical, computer, aeronautical, and material science engineering. In addition to engineers, there was also a small number of industrial design students enrolled in the course. The population was comprised of approximately 90% undergraduate and 10% graduate students.

As the researchers exerted no influence over which students enrolled in which lab sections, there is a level of randomization already built into the assignment of teams and the selection of participants for the control and experimental populations. Two out of the five laboratory sections of ME5682/ISE 5560 were randomly selected to act as the control population, while the remaining three sections represented the experimental population, which used the CCMT. Further, within each section the composition of the student teams of three to four students each was randomly assigned. Rather than randomly assigning the CCMT to groups across all five labs, each section contained either all experimental groups or all control groups, rather than a mixed population. This was done in order to limit cross–contamination of the two populations, and to limit the control groups' knowledge of and exposure to the CCMT as much as possible. Control and experimental groups were run simultaneously rather than the sequential testing of a single population—in which a single population performs a design task first without the benefit of the CCMT, and then again with the CCMT. This was done in order to limit the effects of learning from one design process to the next, which could potentially skew the data. To state another way, control groups were used in order to not positively count the natural learning associated with executing a design process as a benefit of the CCMT's use.

The entire student population of ME5682/ISE 5560 was comprised of approximately 107 students. As all members of the enrolled student population of ME5682/ISE 5560 are representative of the intended student audience, there was no need to exclude any subjects from the research. Students, however, were provided with informed consent forms (which can be seen in *Appendix G*), and given the opportunity to opt out of the research if they chose. If students opted out, student data was not collected, and they were provided with an alternative exercise in lieu of the survey responses. Opting out of the research had no impact on the student's educational program or grade for the course. Despite the fact that there was no risk to the participant population, measures were taken to ensure that individual participants could not be identified. Additionally, students were specifically instructed to not use the names of other students within their responses. Although the student groups' design outcomes were evaluated by a panel of experts, student grades were in no way affected by the results of the study. To ensure this, all evaluations occurred after the conclusion of the semester and submission of student grades.

For the purposes of this study, the experimental population consisted of those students who used the CCMT within their design processes, and the control population consisted of students who did not. These two populations represented the independent study variable, and no participant took part in more than one group. After students who did not complete all three survey parts were removed from the study, the experimental population contained 60 students (N=60), and the control population contained 37 students (N=37). All of the statistical tests used to analyze the collected data account for this difference in population size.

7.1.5 Measurement

The primary variables of interest for this study were: (a) students' attitudes and perceptions about their design process and the CCMT, (b) the impact of the CCMT on teamwork and coordination within trans-disciplinary groups, (c) the impact of the CCMT on the students' understanding of their chosen design problem, context, and relevant stakeholders, and (d) the impact of the CCMT on the overall quality of the students' designed solutions. Variables (a), (b), and (c) were assessed through the use of weekly surveys and informal interactions with participants. Because of the subjective nature of both design and design education, highly data-driven measures were infeasible and unlikely to provide a realistic or meaningful picture of the value of any new educational strategy. The surveys themselves were instead a mix of Likert–type item ratings and informal written feedback and comments.

A Likert item is a statement which the respondent is asked to evaluate according to any kind of subjective or objective criteria. These questions typically measure the respondent's level of agreement or disagreement. It is generally considered to be symmetric or "balanced" as there are an equal number of positive and negative positions. Although these measurements can be measured using a seven or nine level scale, five ordered response levels are typically used [290]. Likert scales are a popular and appropriate data-gathering tool for questionnaire based research, and are the most widely–used scale in survey research. Despite their widespread use, Likert scale items may be subject to distortion from several causes: respondents may avoid using extreme response categories (central tendency bias), agree with statements as presented (acquiescence bias), or try to portray themselves more positively (social desirability bias). Using a scale with an

equal number of positive and negative responses can lessen some of these problems, but will never eliminate them entirely [291].

Three surveys were longitudinally distributed over the course of the project: one near the beginning, one at the mid-point, and one at the conclusion of the project. This was done to assess the effects of the CCMT over time, how the students' opinions of the tool changed over the course of the project, and how it affected students' collaboration and team-work. Each of these surveys can be found in *Appendix B*. The survey results are reviewed, categorized, and presented to provide the most accurate assessment of the CCMT's value and outcomes as possible.

To ascertain the CCMT's effect on the students' design solutions, a panel of experts from the fields of engineering and design were asked to assess the final design solutions of each group. The design expert population consisted of 26 individuals with a wide range of expertise and experience: Of the 26, seven self–identified as engineers, eleven as design engineers, and eight as designers. The experience of these individuals ranges from 1.5 to 43 years with an average of 12.75, and a median of 11. The qualitative assessments of a design's quality were completed by assigning each design a score on a numerical rating scale. Additional evaluations were performed using Likert items, and intended to assess the design students' understanding of the design context, the creativity exhibited, and the solution's innovation potential. An open-ended evaluation was also included, intended to capture the strengths and weaknesses of each design that could not be captured using the numerical scales. While participation posed no risk to the expert evaluators, their identities were also protected. The final evaluator survey and results can be seen in *Appendix H* and *Appendix I*.

In order to make the task of evaluating student projects more manageable and time efficient for the expert evaluators, the set of thirty student design projects was halved. This was a considered decision made in order to reduce the time of evaluation from approximately five hours, and intended to elicit as much participation as possible. The decision was made in order to prioritize the number of expert evaluations over the assessment of all thirty projects, since asking busy design practitioners for such a large amount of time was unlikely to be met with a great deal of participation. In halving the student sample, the original 16:11 ratio between experimental and control groups (1.64:1), was maintained as closely as possible; the final evaluation packet consisted of nine experimental projects and six control projects (a ratio of

1.5:1). The selection of the projects to include in the evaluation packet was random within each population.

To ensure consistency of the data, the same group of experts evaluated all of the designs, and the numerical rating scale was augmented with qualitative descriptions in order to attempt to improve the commonality of the data. These numerical scores and the qualitative feedback were then used in order to develop an aggregate understanding of the impacts that the new educational strategy had on the quality of student designs. At the time of evaluation, all of the student designs—from both populations—were presented in an identical two-page format, and evaluators were unaware which population (test or control) a particular design represented—this was done by randomizing the order in which the designs were presented to evaluators. Further, to ensure that the evaluator results were not biased based upon the order in which the designs were reviewed, multiple versions of the evaluation packets were distributed—each ordered in a different way.

7.1.6 Implementation: Limitations and Observations

In order to provide the opportunity for the CCMT to be used to its fullest potential, steps were taken to ensure that the students understood the value of the tool, how it was to be used, and the role it could play within their design processes. Despite this, there were aspects of the tool's implementation that may have limited and affected the outcomes of the study. These aspects of implementation within the classroom setting are discussed here, in addition to a few more general comments about the process.

The tool was initially introduced to the experimental sections with a short presentation in which the tool was explained and demonstrated. The tool's functionality (provided capabilities) and use were both covered in this presentation. Although the large majority of participants were already comfortable with the use of Microsoft Excel, the demonstration was not effective in conveying a full understanding of the tool. In many ways, students could only develop a good sense of the tool through actual use. Even in combination with the included documentation and instructions, the presentation was still a less than ideal way to transfer knowledge about the tool's capabilities and usage. The study was conducted during the second of two design projects within the course, as the second project was both longer and conducted

within a real-world design setting. But in retrospect, it might have been more beneficial if the tool had been introduced within the first design process in order to allow the students to gain a level of familiarity with the CCMT, before evaluating its use within a second design project.

In its current form, the CCMT is not set up for truly collaborative editing. The fact that a CCMT matrix is associated with a single Excel file, led to situations in which the file was located on the computer of a single team member. While this does not necessarily preclude collaborative work, it is a potential hindrance. In some situations, a single team member emerged as the CCMT "expert," responsible for updating and changing the file. In other groups, collaboration occurred more effectively. In these instances, the CCMT was populated primarily in a group setting with all team members participating and offering opinions and insights. The latter case is much closer to the desired operation of the tool, with consensus opinions being used to populate the constraints, weights, interaction values, etc.

In an effort to encourage students to integrate the CCMT into their design processes in a meaningful way, rather than simply populating the matrix at the end of their process, students were asked to bring an up–to–date version of their matrix with them to each class. Within the experimental sections, the CCMT was used to guide the discussion of the design problem as much as possible. Despite these efforts, however, some student teams clearly did not prioritize the use of the tool, and showed little interest in populating the matrix. While completion of the matrix was mandatory once a group elected to participate in the study, the fact that the CCMT was not graded led to a reduced incentive to put forth additional effort. This resulted in an uneven leveraging of the tool across groups, as certain groups attempted to implement the tool in a much deeper way than others.

This can be evidenced in contrasting many of the completed student matrices, which can be seen in *Appendix J*. Some of the completed matrices are much more thoroughly populated than others, just as some groups relied on the matrix more than others. While it would have been ideal to have more equal reliance on the tool, any measures to do so—assigning a grade for the CCMT, for example—would likely have resulted in an artificial and potentially misleading view of the CCMT's value with respect to the actual design process. At the same time, this asymmetric effort is indicative of a broader reality within design education: certain students, and certain teams are always more engaged than others, and engaged groups by definition are more willing to invest time and effort than those that are not. This certainly had an effect on the data,

but the assumption is that this effect was consistent across both control and experimental sections.

Because of the time pressures present within the class—the lab met only once a week, with an average of six groups per one-hour and forty-eight minute lab—there was not always sufficient time to discuss the CCMT. It is very likely that questions and opportunities about the tool's population and relevance within the design process went unaddressed. This is certainly true from the research perspective, but was also recognized by a number of the students, many of who were intrigued by the potential value of the CCMT but were still uncertain as to how it could be best leveraged within the process. This sentiment was commonly expressed in both informal discussions and survey responses; one student noted that, "it [the CCMT] was helpful, but it would have been more useful with more instruction on how to apply it to our design."

Another limitation is that because of the length of the project, this particular study does not capture all of the activities and considerations that affect real-world design processes. Parts of the CCMT (e.g. the expected rate of change column, and even the stakeholder column) were underutilized as a result of the truncated nature of the design project. Accordingly, all of the features of the CCMT were not equally valuable. The student projects were focused on identifying relevant design problems and developing novel design concepts, but there was often little time to consider the finer details of a design's execution. Product architecture, manufacturing, tolerances, and even the precise mechanical design of a solution were left largely unconsidered. In contrast, real-world design process must consider all of these factors in order to develop successful design solutions.

Finally, because of the constantly changing nature of the design process, student understandings and opinions are rarely static. This made assessing any measure of test/retest reliability difficult to achieve, and it was therefore difficult to show statistical *repeatability* or assess the quality of the surveys or the individual survey questions. The initial study made no attempts to assess the intra-individual variability of the student respondents; steps were taken to do so in a follow-up study conducted with a much smaller sample population composed of graduate students (N=11). In this instance, the respondents were asked to take the initial survey twice: once immediately upon being introduced to the matrix, and once a few days later prior to beginning any project work. Intra–class correlation (ICC) was determined for each of the questions in an attempt to determine its reproducibility. The ICC's and 95% confidence intervals

for each of the survey 1 questions were as follows: 0.935 [0.759, 0.983], 0.884 [0.570, 0.969], 0.946 [0.800, 0.986], and 0.962 [0.860, 0.990]. While this is still a wholly imperfect way to assess the repeatability of the study (small sample size and a different population), these results indicate that each of the questions on the first survey were repeatable for the same items under *similar* conditions.

7.2 Data Analysis Procedures

As indicated, the majority of survey responses were collected using Likert scale items. This was done in order to attempt to assess ideas, understandings, thoughts, and evaluations that are typically difficult to quantify. While collecting data in this fashion is appropriate for the given study, there are still challenges associated with this approach. The chosen data analysis methods are intended to give an evaluation of the tool that is as honest as possible. While any single method is unlikely to provide an accurate view of the tool or its effectiveness, a combination of methods can provide a better picture of the ways in which the CCMT *actually* affected the students' design process. In this instance, the data (which can be seen in *Appendix I*) will be described using a combination of visual representation and assessment, basic descriptive statistics, and more detailed statistical tests. Each of these methods allows the data to be understood in a slightly different way, and together they allow us to synthesize a better sense of the tool's impact.

Before each of the data analysis methods can be discussed, however, it is necessary to discuss the nature of measurements acquired using Likert items, as this will have implications for how the data are handled. Most notably, Likert scale items produce ordinal, non-interval data. Individual responses to Likert items are typically treated as *ordinal data* because the responses have relative positions, but we cannot presume that the difference between adjacent levels is equal (a requirement for interval data). The difference between a score of '4' and '5', or 'positive' and 'most positive,' is not necessarily perceived by respondents to be proportional to the difference between 'neutral' and 'positive' ('3' and '4'). While Likert scale responses can *approximate* interval data, treating it as such can lead to misrepresentations of the underlying data, from a statistical standpoint [292].

As a result, mean and standard deviation are inappropriate parameters for descriptive statistics on ordinal Likert items, as are parametric analyses based upon the normal distribution [293]. Because of the ordinal nature of Likert items, central tendency is best described using median or mode, with a spread measured using quartiles. Further, non-parametric tests should be preferred over parametric analyses such as ANOVA and T-tests as inferential techniques [294]. Because the data is ordinal and non-interval, the following descriptive techniques will be used to analyze the study results:

a. Bar charts measuring the frequency of responses will be used in favor of histograms, because the data is not continuous.
b. Central tendency will be measured using median and mode rather than mean. Although the mean will be provided in order to help better describe the data, it will not be used for any measures of statistical significance.
c. Instead of using standard deviation, variability will be summarized by providing the minimum and maximum values (defining the range) and the inter-quartile range.

The first and most basic component of this data analysis is clustering and visual representation. As much as possible, related survey questions have been grouped together in order to allow the comparison of relevant data. Combined with quick visual representations, this represents the first level of analysis which allows the reader to begin to compare data across questions, test populations, and longitudinal surveys. Accordingly, survey results will be presented sequentially (survey 1, survey 2, survey 3) and as a direct comparison between experimental (CCMT) and control data, as appropriate. While this is not always possible (because a question did not appear on all three surveys, or was only asked to one population), this format will be followed as closely as possible. Frequency–sorted comparison bar charts are used to visually present the data, and percentages rather than numerical counts are displayed in order to account for differing population sizes. All visual representations are intended to describe the data as accurately as possible. Basic descriptive statistics and measures are included for each survey question, and are used in conjunction with the visual representations in order to allow the reader to gain a deeper understanding of the data. Median, mode, and mean are provided to show central tendency and spread is indicated by inter-quartile range.

It is also necessary to subject the data to statistical tests and analysis in order to provide statistically significant results. For the purposes of this study the data was analyzed using three

non-parametric tests: the Mann-Whitney U test intended to assess distributions between unrelated populations; the Friedman test intended to assess the similarity of distributions across three or more related groups; and the Wilcoxon Signed-Rank test intended to determine differences across two related groups. Each of these tests was selected for its appropriateness for the given data and associated collection methods, and is discussed more thoroughly below.

7.2.1 Mann-Whitney U test

The *Mann-Whitney U test* determines whether there is a statistically significant difference between the distributions of two independent groups (experimental and control). It is the nonparametric alternative to the independent-samples t-test [295]. In order to be used, the Mann-Whitney U test requires that certain assumptions are met:

1. The dependent variable should be *ordinal* or *interval*—Likert scale items produce ordinal data.
2. The independent variable consists of *two categorical, independent groups*—satisfied by the independent experimental and control populations.
3. *Independence of observation*, meaning that there is no relationship between the observations in each group or between the groups themselves—each study participant is a member of only one test population.
4. The Mann-Whitney U test does not require data that is normally distributed, but both distributions should be of the same shape—satisfied by the presented data.

The null and alternative hypotheses for the Mann-Whitney U test are:

H_0: the distribution for the two groups is the same

H_A: the distribution for the two groups is different

In general, the Mann-Whitney U test is used between test populations to determine if the two data sets belong to the same distribution. Within this study, it will be used to determine if there is a statistically significant difference *between* the two groups (experimental and control) for a single question that was asked to both populations.

7.2.2 *Friedman test*

The *Friedman test* determines whether there are any statistically significant differences between distributions of *three or more* related groups. The groups are related as they contain the same participants and each represents a repeated measurement on the same dependent variable. It is a non-parametric alternative to the repeated measures ANOVA test, and is an extension of the Wilcoxon signed-rank test for more than two groups. This test is used for non-normal distributions, or if the dependent variable is measured on an ordinal scale [296]. The Friedman test makes the following assumptions:

1. A single group (experimental or control) that is measured on three or more separate occasions.
2. The dependent variable should be ordinal or interval.

The null and alternative hypotheses for the Friedman test are:

H_0: the distribution for each of the groups is the same

H_A: the distribution for at least two groups is different

The Friedman test is used to determine if a distribution has changed over a period of time, for questions that are asked longitudinally. For this study, it will be used *within* a single test population to test questions that were asked on each of the three surveys (e.g. attitude about the project, teamwork, or CCMT). While the Friedman test can show a change has occurred, it does not show the nature of that change. In the instances where a change has occurred, multiple pair-wise Wilcoxon Signed-Rank tests will then be performed.

7.2.3 *Wilcoxon Signed-Rank test*

The *Wilcoxon Signed-Rank test* determines whether there are significant differences between paired observations. It can be used to compare two independent participants or groups. The participants are either the same individuals tested on two occasions, or under two different

conditions, on the same dependent variable. The Wilcoxon Signed-Rank test is the non-parametric equivalent to the paired-samples t-test [297]. It makes the following assumptions [298]:

1. The dependent variable should be ordinal or interval.
2. The independent variable should consist of two "related groups," meaning that the same subjects are present in both groups. Generally, this entails the same subjects being measured on two occasions, for the same dependent variable.

The null and alternative hypotheses for the Wilcoxon Signed-Rank test are:

H_0: the median difference between the paired data sets is equal to zero

H_A: the median difference between the paired data sets is not equal to zero

The Wilcoxon Signed-Rank test will be used to determine if the distribution has changed for a single population across *two* measurements over time. It is suitable for measuring if a variable has changed over time in the same subjects, and can indicate the nature of this change. Accordingly, it will be used in a pairwise fashion for instances where the Friedman test has returned a significant result, as well as for determining if there is a difference between questions that were only asked on two occasions (two of the three surveys).

7.3 Data Analysis: Student Participant Results

This section covers the results of the three longitudinal student surveys, across the experimental (N=60) and control (N=37) populations. To reiterate, the experimental population was provided with the Concurrent Constraint Matrix Tool and instruction on its use; the control population completed the design project according to pre-existing procedures. The following questions are grouped in order to better describe and compare the data. When applicable, questions will be compared across study populations as well as over the course of the project (represented by the three sequentially administered surveys). Each question will be briefly introduced prior to the presentation of the data analysis, and each section will conclude by

providing context, discussing the relevance of the data, and suggesting possible explanations for observed results.

7.3.1 Student Attitudes about Teamwork

The prompt, "please rate your current attitude about the quality of your group's teamwork" was given to both experimental and control populations on each of the three surveys. Responses were recorded using a Likert scale ranging from 1-5, with 1 representing "most negative" and 5 being "most positive." Results are first compared across populations for each of the three surveys, and then compared across the three surveys for a single population.

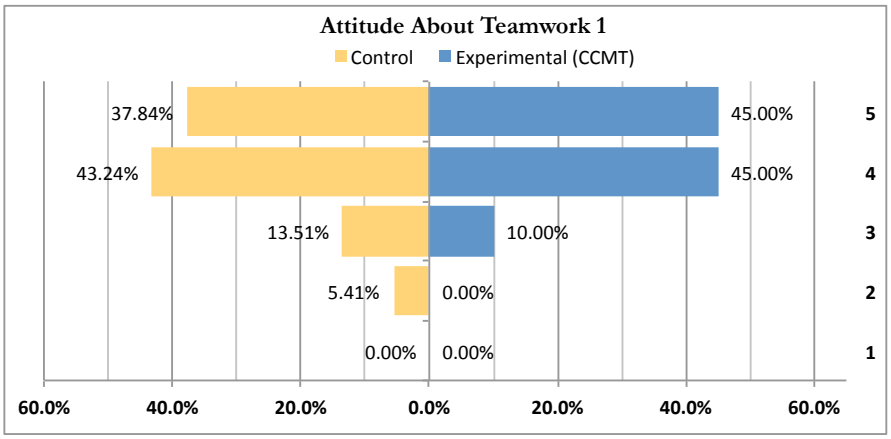


Figure 7.1: Frequency sorted responses for student attitude about teamwork (survey 1).

	Control		Experimental (CCMT)	
Min:	2		3	
Max:	5		5	
Median:	4		4	
Mode:	4		5	
Mean:	4.135		4.350	
Quartile 1:	4		4	
Quartile 3:	5		5	
IQR:	1		1	
Frequency sorted responses				
1:	0	0.00%	0	0.00%
2:	2	5.41%	0	0.00%
3:	5	13.51%	6	10.00%
4:	16	43.24%	27	45.00%
5:	14	37.84%	27	45.00%

Table 7.1: Descriptive statistics for student attitude about teamwork (survey 1).

To compare the distributions between experimental and control populations, a Mann-Whitney U test was run to determine if there were differences in the attitude toward teamwork between individuals who used the CCMT and those who did not. For survey 1 (*Figure 7.1*, *Table 7.1*), given near the outset of the project, there was no statistically significant difference between the control (Mdn = 4) and the experimental (Mdn = 4) population; $U = 1242$, $z = 1.072$, and $p = 0.284$ (for a given significance level of 0.05).

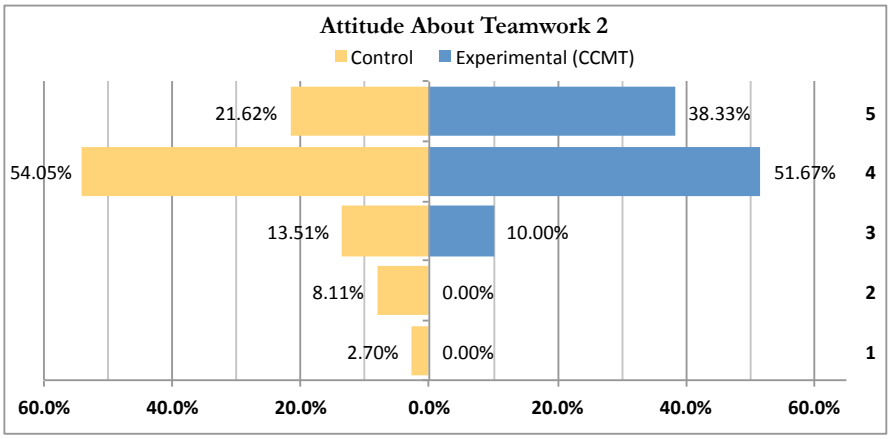


Figure 7.2: Frequency sorted responses for student attitude about teamwork (survey 2).

	Control		Experimental (CCMT)	
Min:	1		3	
Max:	5		5	
Median:	4		4	
Mode:	4		4	
Mean:	3.838		4.283	
Quartile 1:	4		4	
Quartile 3:	4		5	
IQR:	0		1	
Frequency sorted responses				
1:	1	2.70%	0	0.00%
2:	3	8.11%	0	0.00%
3:	5	13.51%	6	10.00%
4:	20	54.05%	31	51.67%
5:	8	21.62%	23	38.33%

Table 7.2: Descriptive statistics for student attitude about teamwork (survey 2).

For survey 2 (*Figure 7.2*, *Table 7.2*), given near the midpoint of the project, the respondents' attitudes towards their group's teamwork differed in a statistically significant way

between the control and the experimental population; $U = 1387$, $z = 2.271$, and $p = 0.023$ (for a given significance level of 0.05).

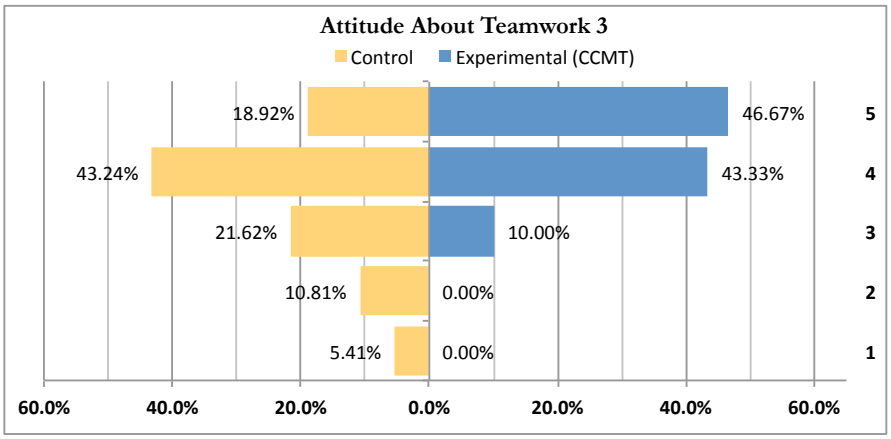


Figure 7.3: Frequency sorted responses for student attitude about teamwork (survey 3).

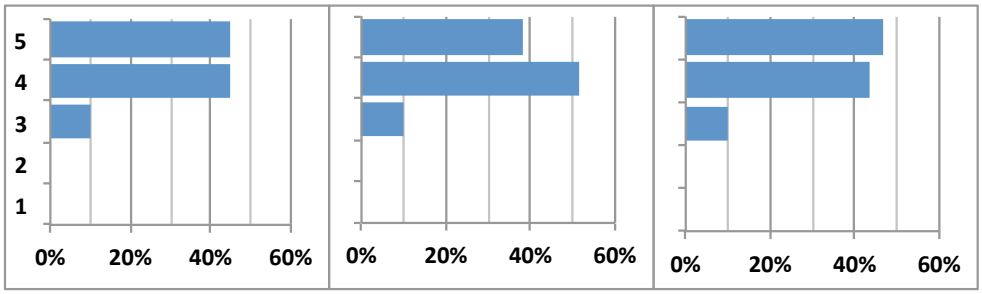
	Control		Experimental (CCMT)	
Min:	1		**Min:**	3
Max:	5		**Max:**	5
Median:	4		**Median:**	4
Mode:	4		**Mode:**	5
Mean:	3.595		**Mean:**	4.367
Quartile 1:	3		**Quartile 1:**	4
Quartile 3:	4		**Quartile 3:**	5
IQR:	1		**IQR:**	1
Frequency sorted responses			**Frequency sorted responses**	
1:	2	5.41%	**1:**	0	0.00%
2:	4	10.81%	**2:**	0	0.00%
3:	8	21.62%	**3:**	6	10.00%
4:	16	43.24%	**4:**	26	43.33%
5:	7	18.92%	**5:**	28	46.67%

Table 7.3: Descriptive statistics for student attitude about teamwork (survey 3).

For survey 3 (*Figure 7.3*, *Table 7.3*), given at the conclusion of the project, the respondents' attitudes towards their group's teamwork differed in a statistically significant way between the control and the experimental population; $U = 1570$, $z = 3.665$, and $p = < 0.005$ (for a significance level of 0.05).

In order to assess if the students' attitudes changed over time within each population, a Friedman test was run to determine if the distribution is the same across all three time periods for each independent group. For the experimental (CCMT) population (*Figure 7.4*), a Friedman

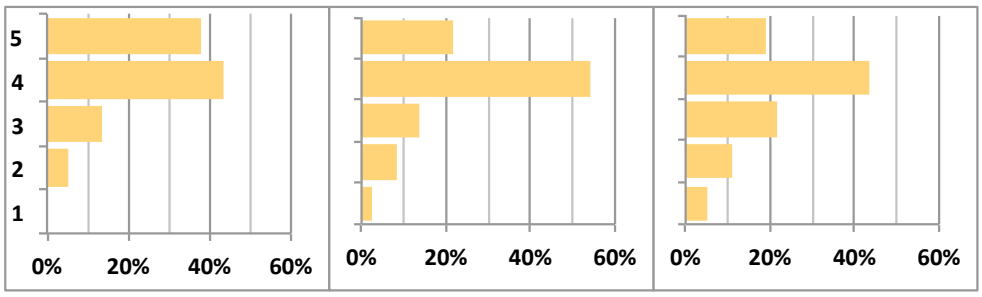
test was run to determine differences across the entire project. Any differences were not statistically significant, $\chi^2(2) = 0.742$, $p = 0.690$; where '(2)' refers to the degrees of freedom, '0.742' is the test statistic. Therefore we accept the null hypothesis that the distributions for the experimental population did not change significantly over the course of the project.



Experimental Survey 1		Survey 2		Survey 3	
Median:	4	**Median:**	4	**Median:**	4
Mode:	5	**Mode:**	4	**Mode:**	5
Mean:	4.350	**Mean:**	4.283	**Mean:**	4.367
Quartile 1:	4	**Quartile 1:**	4	**Quartile 1:**	4
Quartile 3:	5	**Quartile 3:**	5	**Quartile 3:**	5
IQR:	1	**IQR:**	1	**IQR:**	1

Figure 7.4: Comparing frequency sorted responses and descriptive statistics for attitude about teamwork across the three surveys (experimental).

Doing the same test for the control population (*Figure 7.5*) reveals attitudes towards teamwork were statistically significantly different over the course of the project, $\chi^2(2) = 11.256$, $p = 0.004$ (for a significance level of 0.05).



Control Survey 1		Survey 2		Survey 3	
Median:	4	**Median:**	4	**Median:**	4
Mode:	4	**Mode:**	4	**Mode:**	4
Mean:	4.135	**Mean:**	3.838	**Mean:**	3.595
Quartile 1:	4	**Quartile 1:**	4	**Quartile 1:**	3
Quartile 3:	5	**Quartile 3:**	4	**Quartile 3:**	4
IQR:	1	**IQR:**	0	**IQR:**	1

Figure 7.5: Comparing frequency sorted responses and descriptive statistics for attitude about teamwork across the three surveys (control).

In order to better assess where the differences exist within the control population, multiple pairwise Wilcoxon Signed-Rank tests were performed. Because there is not a statistically significant difference across the project for the experimental (CCMT) groups, this step was not necessary for that population. Running the Wilcoxon Signed-Rank test for the control population yielded a statistically significant decrease for 'attitude towards teamwork' between the beginning (survey 1) and middle (survey 2) of the project, $z = -2.076$, $p = 0.038$ (for a significance level of 0.05). Running the test again between the middle (survey 2) and end of the project (survey 3), there appears to be a continued decrease in the 'attitude towards teamwork', but it is not statistically significant, $z = -1.427$, $p = 0.154$.

At the outset of the project, the students using the CCMT (experimental) and those who were not (control) had a similarly positive attitude towards their group's teamwork. As the project progressed, the groups using the CCMT maintained a similarly positive attitude throughout. The attitude of the groups not using the CCMT, however, degraded over the duration of the project in a significantly significant way. This indicates that the use of the CCMT had a positive impact on the group's ability to communicate, share ideas, and make decisions in a way that helped to maintain a more positive attitude towards teamwork.

7.3.2 Shared Understanding of the Design Problem

When attempting to design in a collaborative team setting, team members frequently have different views about the design problem, what is important, and what needs to be considered and addressed in order to reach a solution. One of the potential values of the CCMT is to encourage design teams and organizations to develop a shared view of the problem. In order to assess this, students in both control and experimental populations were asked to rate the degree to which their team "…shares an understanding of the design problem, its relevant factors, and what needs to be done to successfully complete this project." Responses were recorded using a Likert scale ranging from 1-5, with 1 representing "completely different" and 5 being "totally shared." As students had not yet identified the design problems they were going to solve at the outset of the project, this question only appeared on surveys two and three. Results will be first compared across populations for each of the surveys, and then compared across surveys for a single population.

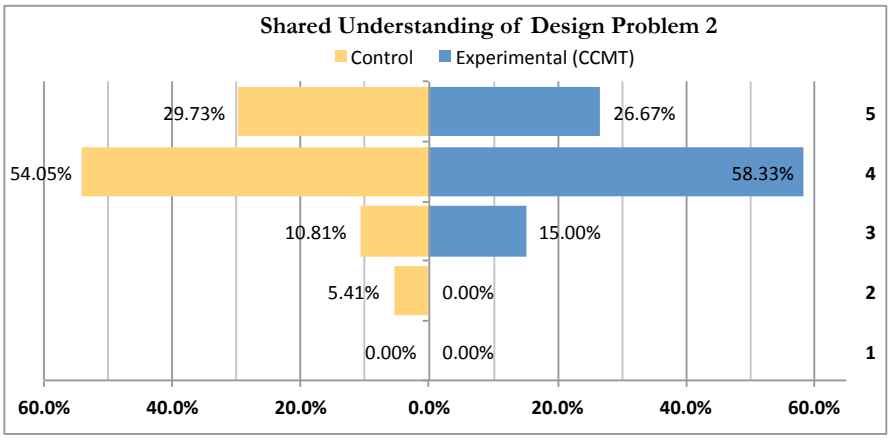


Figure 7.6: Frequency sorted responses for team's shared understanding of the design problem (survey 2).

	Control		Experimental (CCMT)	
Min:	2		3	
Max:	5		5	
Median:	4		4	
Mode:	4		4	
Mean:	4.081		4.117	
Quartile 1:	4		4	
Quartile 3:	5		5	
IQR:	1		1	
Frequency sorted responses			**Frequency sorted responses**	
1:	0	0.00%	**1:** 0	0.00%
2:	2	5.41%	**2:** 0	0.00%
3:	4	10.81%	**3:** 9	15.00%
4:	20	54.05%	**4:** 35	58.33%
5:	11	29.73%	**5:** 16	26.67%

Table 7.4: Descriptive statistics for team's shared understanding of the design problem (survey 2).

To compare the distributions between populations, a Mann-Whitney U test was run to determine if there were differences in the students' views about the degree to which their team shared an understanding of the design problem between individuals who used the CCMT and those who did not. For survey 2 (*Figure 7.6*, *Table 7.4*), the respondents' attitudes did not differ in a statistically significant way between the control and the experimental population; $U = 1100$, $z = -0.083$, and $p = 0.934$ (for a significance level of 0.05). For survey 3 (*Figure 7.7*, *Table 7.5*), the respondents' attitudes differed in a statistically significant way between populations; $U = 1767$, $z = 5.309$, and $p = < 0.005$ (for a significance level of 0.05).

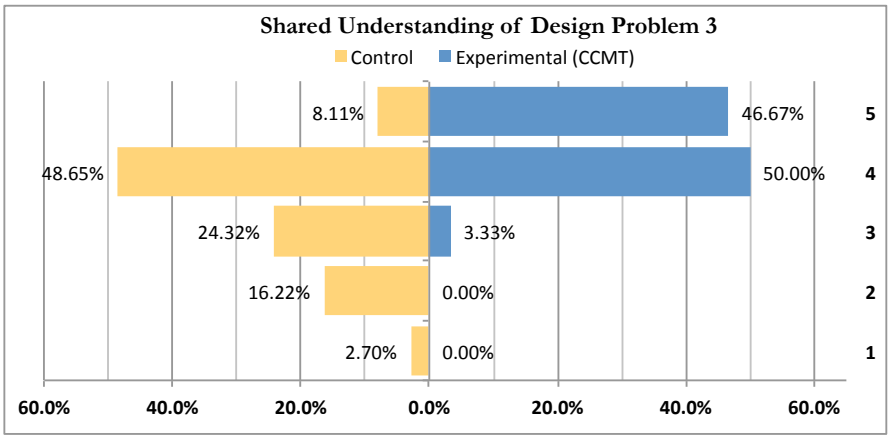
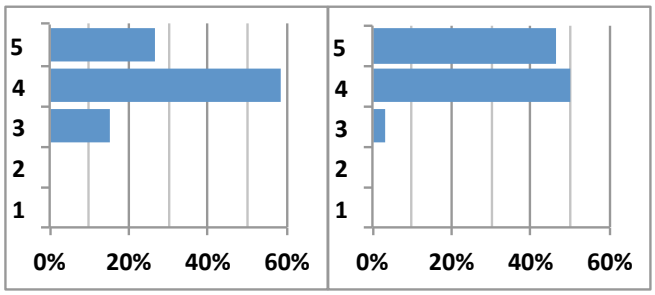


Figure 7.7: Frequency sorted responses for team's shared understanding of the design problem (survey 3).

Control			Experimental (CCMT)		
Min:	1		**Min:**	3	
Max:	5		**Max:**	5	
Median:	4		**Median:**	4	
Mode:	4		**Mode:**	4	
Mean:	3.432		**Mean:**	4.433	
Quartile 1:	3		**Quartile 1:**	4	
Quartile 3:	4		**Quartile 3:**	5	
IQR:	1		**IQR:**	1	
Frequency sorted responses			**Frequency sorted responses**		
1:	1	2.70%	**1:**	0	0.00%
2:	6	16.22%	**2:**	0	0.00%
3:	9	24.32%	**3:**	2	3.33%
4:	18	48.65%	**4:**	30	50.00%
5:	3	8.11%	**5:**	28	46.67%

Table 7.5: Descriptive statistics for team's shared understanding of the design problem (survey 3).

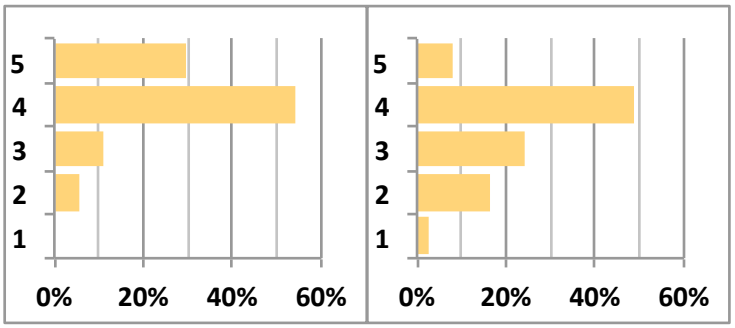
In order to assess if the students attitudes changed over time within each population, a Wilcoxon Signed-Rank test was run for each independent group to determine if the distribution was the same across both surveys. Running the Wilcoxon Signed-Rank test for the experimental population (*Figure 7.8*) yielded a statistically significant increase for 'shared understanding' between the two surveys; $z = 3.210$, $p = 0.001$ (for a significance level of 0.05). There were $N = 23$ positive differences, $N = 6$ negative differences, and $N = 31$ ties between the surveys.



Experimental Survey 2		Survey 3	
Median:	4	**Median:**	4
Mode:	4	**Mode:**	4
Mean:	4.117	**Mean:**	4.433
Quartile 1:	4	**Quartile 1:**	4
Quartile 3:	5	**Quartile 3:**	5
IQR:	1	**IQR:**	1

Figure 7.8: Comparing frequency sorted responses and descriptive statistics for understanding of the design problem (experimental).

Running the Wilcoxon Signed-Rank test again for the control population (*Figure 7.9*) reveals a statistically significant decrease in 'shared understanding' between the two surveys; $z = -3.594$, $p = < 0.005$ (for a significance level of 0.05). There were $N = 4$ positive differences, $N = 22$ negative differences, and $N = 11$ ties between the surveys.



Control Survey 2		Survey 3	
Median:	4	**Median:**	4
Mode:	4	**Mode:**	4
Mean:	4.081	**Mean:**	3.432
Quartile 1:	4	**Quartile 1:**	3
Quartile 3:	5	**Quartile 3:**	4
IQR:	1	**IQR:**	1

Figure 7.9: Comparing frequency sorted responses and descriptive statistics for understanding of the design problem (control).

When the teams' shared understandings were first addressed on survey two, there was not a statistically significant difference between the groups using the CCMT and those who were not. Students generally felt that they shared a similar view of the design problem, its important factors, and what needed to be done to reach a solution with their teammates. As the project progressed, however, the two groups diverged significantly. The shared understanding of those using the CCMT improved from the mid-point of the project to its conclusion, while the shared understanding of those not using the CCMT regressed. This indicates that the CCMT had a positive impact on the ability of the groups to continue to develop a shared understanding of the design problem. There may be a number of reasons for this, but is likely related to the necessity to explicitly discuss the design constraints and negotiate their value within the group.

7.3.3 *Ability to Reach a Consensus Solution*

Similar to the ability to develop a shared understanding, students were asked to rate the degree to which their "…group's final solution represent[ed] a consensus solution to the design problem." This question was intended to determine if the team members were in agreement with regard to the nature and direction of their final solution. Responses were recorded using a Likert scale ranging from 1-5, with 1 representing "no consensus" and 5 being "complete consensus." Since this question could only be asked after a solution had been reached, it only appeared on survey three. Results are compared across both populations (*Figure 7.10*, *Table 7.6*).

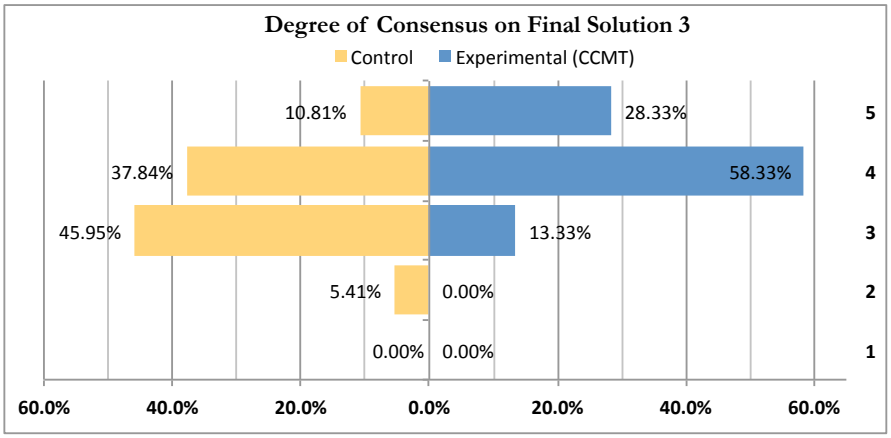


Figure 7.10: Frequency sorted responses for degree of consensus (survey 3).

	Control		Experimental (CCMT)	
Min:	2		**Min:**	3
Max:	5		**Max:**	5
Median:	3		**Median:**	4
Mode:	3		**Mode:**	4
Mean:	3.541		**Mean:**	4.150
Quartile 1:	3		**Quartile 1:**	4
Quartile 3:	4		**Quartile 3:**	5
IQR:	1		**IQR:**	1
Frequency sorted responses			**Frequency sorted responses**	
1:	0	0.00%	**1:**	0	0.00%
2:	2	5.41%	**2:**	0	0.00%
3:	17	45.95%	**3:**	8	13.33%
4:	14	37.84%	**4:**	35	58.33%
5:	4	10.81%	**5:**	17	28.33%

Table 7.6: Descriptive statistics for degree of consensus (survey 3).

To compare the distributions between experimental and control groups, a Mann-Whitney U test was run to determine if there were differences between the two populations with regard to the students' views about the ability of their team to reach a consensus solution to the design problem. The test revealed that the respondents' attitudes differed in a statistically significant way between populations; $U = 1589$, $\chi = 3.872$, and $p = < 0.005$ (for a significance level of 0.05).

While the team's ability to reach a consensus solution is very much tied to their ability to develop a shared understanding of the design problem, this is an encouraging result nonetheless. It indicates that the use of the CCMT increased the likelihood that teams would reach solutions that all of the members were happy with. This is likely because a shared understanding of the design problem can be built upon an agreed upon set of constraints, which provides a shared basis for evaluation of the final solution.

7.3.4 Attitude toward the Design Project

Students from both populations were asked to rate their "…current attitude about [their] design project" on each of the three surveys. Responses were recorded using a Likert scale ranging from 1-5, with 1 representing "most negative" and 5 being "most positive." Results will be first compared across populations for each of the three surveys, and then compared across the three surveys for a single population.

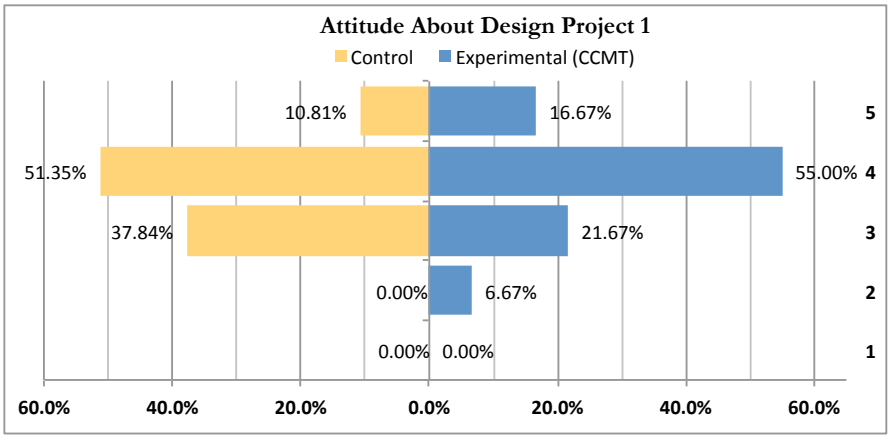


Figure 7.11: Frequency sorted responses for attitude about design project (survey 1).

Control			Experimental (CCMT)		
Min:	3		**Min:**	2	
Max:	5		**Max:**	5	
Median:	4		**Median:**	4	
Mode:	4		**Mode:**	4	
Mean:	3.730		**Mean:**	3.817	
Quartile 1:	3		**Quartile 1:**	3	
Quartile 3:	4		**Quartile 3:**	4	
IQR:	1		**IQR:**	1	
Frequency sorted responses			**Frequency sorted responses**		
1:	0	0.00%	**1:**	0	0.00%
2:	0	0.00%	**2:**	4	6.67%
3:	14	37.84%	**3:**	13	21.67%
4:	19	51.35%	**4:**	33	55.00%
5:	4	10.81%	**5:**	10	16.67%

Table 7.7: Descriptive statistics for attitude about design project (survey 1).

To compare the distributions between populations, a Mann-Whitney U test was run to determine if there were differences in attitude between individuals who used the CCMT and those who did not. For survey 1 (*Figure 7.11*, *Table 7.7*), given near the outset of the project, there was no statistically significant difference between the control and the experimental population; $U = 1216.5$, $z = 0.873$, and $p = 0.383$ (for a given significance level of 0.05). Mann-Whitney U tests run for survey 2 (*Figure 7.12*, *Table 7.8*) and survey 3 (*Figure 7.13*, *Table 7.9*) also yielded no statistically significant differences between distributions for the two populations. Survey 2: $U = 1237$, $z = 1.041$, and $p = 0.298$; and survey 3: $U = 1214.5$, $z = 0.872$, and $p = 0.383$. Bar charts and descriptive statistics can be seen below.

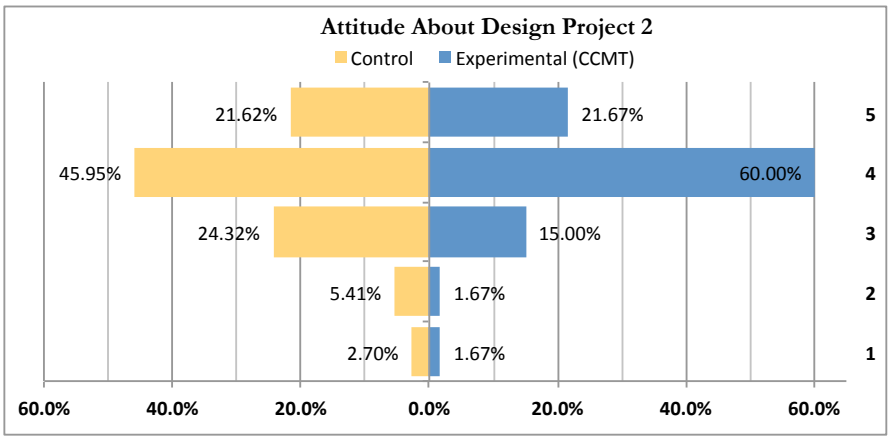


Figure 7.12: Frequency sorted responses for attitude about design project (survey 2).

Control	
Min:	1
Max:	5
Median:	4
Mode:	4
Mean:	3.784
Quartile 1:	3
Quartile 3:	4
IQR:	1

Frequency sorted responses		
1:	1	2.70%
2:	2	5.41%
3:	9	24.32%
4:	17	45.95%
5:	8	21.62%

Experimental (CCMT)	
Min:	1
Max:	5
Median:	4
Mode:	4
Mean:	3.983
Quartile 1:	4
Quartile 3:	4
IQR:	0

Frequency sorted responses		
1:	1	1.67%
2:	1	1.67%
3:	9	15.00%
4:	36	60.00%
5:	13	21.67%

Table 7.8: Descriptive statistics for attitude about design project (survey 2).

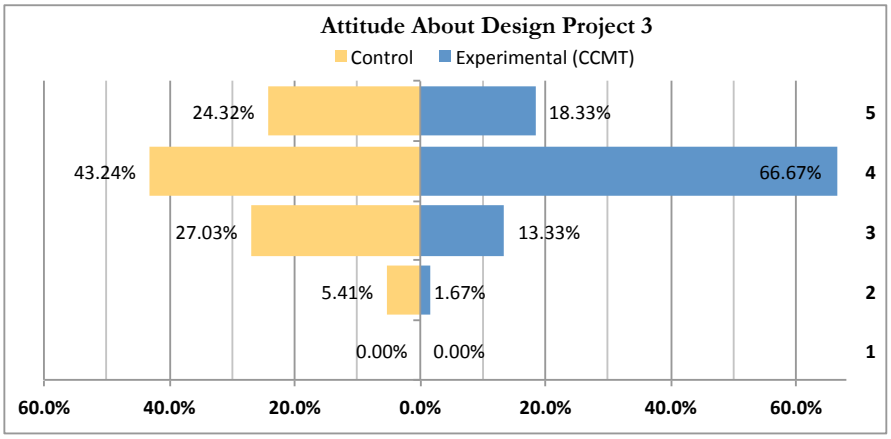


Figure 7.13: Frequency sorted responses for attitude about design project (survey 3).

Control	
Min:	2
Max:	5
Median:	4
Mode:	4
Mean:	3.865
Quartile 1:	3
Quartile 3:	4
IQR:	1

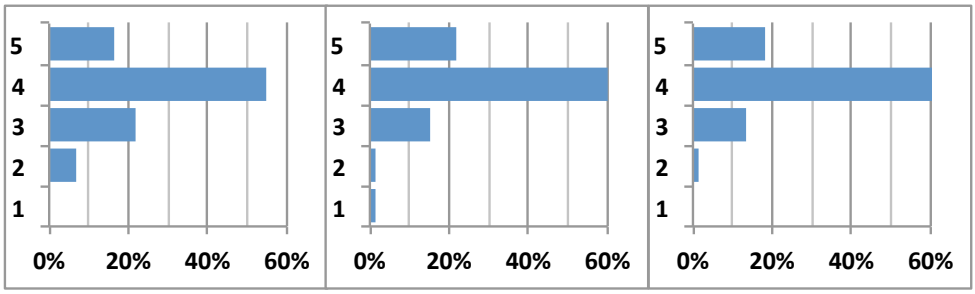
Frequency sorted responses		
1:	0	0.00%
2:	2	5.41%
3:	10	27.03%
4:	16	43.24%
5:	9	24.32%

Experimental (CCMT)	
Min:	2
Max:	5
Median:	4
Mode:	4
Mean:	4.017
Quartile 1:	4
Quartile 3:	4
IQR:	0

Frequency sorted responses		
1:	0	0.00%
2:	1	1.67%
3:	8	13.33%
4:	40	66.67%
5:	11	18.33%

Table 7.9: Descriptive statistics for attitude about design project (survey 3).

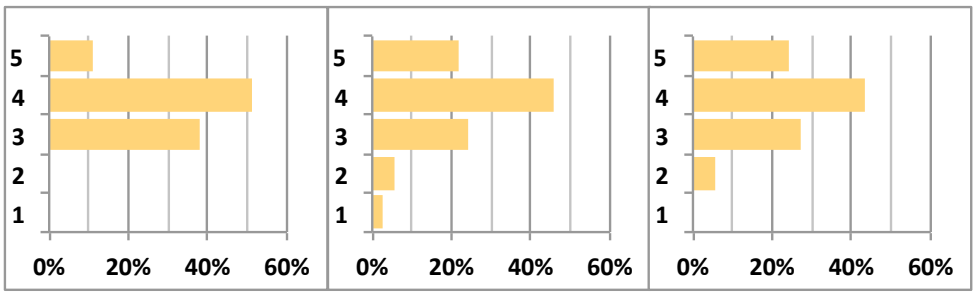
Although there were no statistically significant differences between the test populations, a Friedman test was run to determine if the distributions within the populations changed across the three surveys (three time periods). For the experimental (CCMT) population (*Figure 7.14*), a Friedman test was run to determine differences across the entire project. Any differences were not statistically significant, $\chi^2(2) = 3.023$, $p = 0.221$. Thus we accept that the distributions for the experimental population did not change significantly over the course of the project. Multiple comparisons using the Wilcoxon Signed-Rank test do not need to be performed because the overall test retained the null hypothesis of no differences.



Experimental Survey 1		Survey 2		Survey 3	
Median:	4	**Median:**	4	**Median:**	4
Mode:	4	**Mode:**	4	**Mode:**	4
Mean:	3.817	**Mean:**	3.983	**Mean:**	4.017
Quartile 1:	3	**Quartile 1:**	4	**Quartile 1:**	4
Quartile 3:	4	**Quartile 3:**	4	**Quartile 3:**	4
IQR:	1	**IQR:**	0	**IQR:**	0

Figure 7.14: Comparing frequency sorted responses and descriptive statistics for project attitude (experimental).

For the control (no CCMT) population (*Figure 7.15*), a Friedman test was run, and any differences were once again not statistically significant, $\chi^2(2) = 1.717$, $p = 0.424$. Similar to the experimental population, the distributions for the control group did not change significantly over the course of the project. Multiple comparisons do not need to be performed because the overall test retained the null hypothesis of no differences.



Experimental Survey 1		Survey 2		Survey 3	
Median:	4	**Median:**	4	**Median:**	4
Mode:	4	**Mode:**	4	**Mode:**	4
Mean:	3.730	**Mean:**	3.784	**Mean:**	3.865
Quartile 1:	3	**Quartile 1:**	3	**Quartile 1:**	3
Quartile 3:	4	**Quartile 3:**	4	**Quartile 3:**	4
IQR:	1	**IQR:**	1	**IQR:**	1

Figure 7.15: Comparing frequency sorted responses and descriptive statistics for project attitude (control).

The students' attitudes towards their design projects remained relatively constant and relatively positive throughout the project's duration. The use of the CCMT did not appear to have an impact on this variable. This is not entirely surprising given that the students are generally positive about their own work. Additionally, there are many factors involved in the students' evaluation of their own projects that are unrelated to the CCMT itself.

7.3.5 Understanding of Relevant Stakeholders

In order to assess the effects of the CCMT on the students' understanding of a design's relevant stakeholders, students in both populations were asked to rate their understanding of the "…various stakeholders, and stakeholder needs, that are relevant to [their] project" Responses were recorded using a Likert scale ranging from 1-5, with 1 representing "very limited understanding" and 5 being "detailed and accurate understanding." This question only appeared on surveys two and three. Results will be first compared across populations for each of the surveys, and then compared across surveys for a single population.

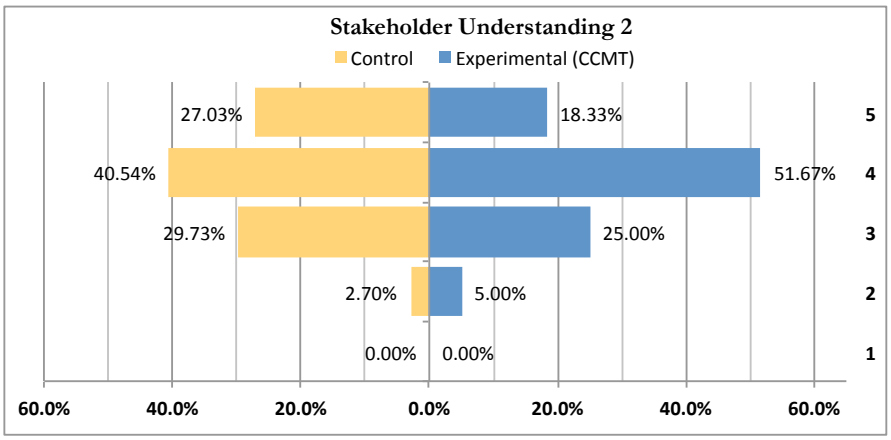


Figure 7.16: Frequency sorted responses for stakeholder understanding (survey 2).

	Control		Experimental (CCMT)	
Min:	2		**Min:**	2
Max:	5		**Max:**	5
Median:	4		**Median:**	4
Mode:	4		**Mode:**	4
Mean:	3.919		**Mean:**	3.833
Quartile 1:	3		**Quartile 1:**	3
Quartile 3:	5		**Quartile 3:**	4
IQR:	2		**IQR:**	1
Frequency sorted responses			**Frequency sorted responses**	
1:	0	0.00%	**1:**	0	0.00%
2:	1	2.70%	**2:**	3	5.00%
3:	11	29.73%	**3:**	15	25.00%
4:	15	40.54%	**4:**	31	51.67%
5:	10	27.03%	**5:**	11	18.33%

Table 7.10: Descriptive statistics for stakeholder understanding (survey 2).

To compare the distributions, a Mann-Whitney U test was run to determine if there were differences in the students' understanding of the relevant stakeholders between individuals who used the CCMT and those who did not. For survey 2 (*Figure 7.16*, *Table 7.10*), the respondents' attitudes did not differ in a statistically significant way between the control and the experimental population; $U = 1055.5$, $z = -0.435$, and $p = 0.663$.

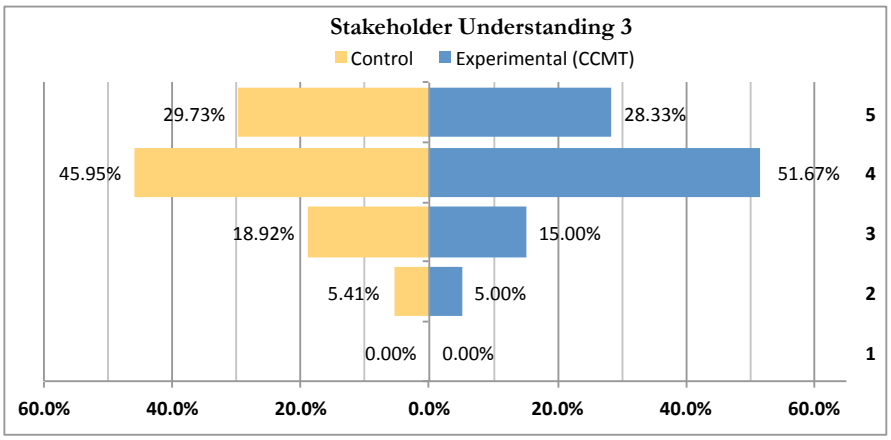


Figure 7.17: Frequency sorted responses stakeholder understanding (survey 3).

	Control		Experimental (CCMT)	
Min:	2		**Min:**	2
Max:	5		**Max:**	5
Median:	4		**Median:**	4
Mode:	4		**Mode:**	4
Mean:	4.000		**Mean:**	4.033
Quartile 1:	4		**Quartile 1:**	4
Quartile 3:	5		**Quartile 3:**	5
IQR:	1		**IQR:**	1
Frequency sorted responses			**Frequency sorted responses**	
1:	0	0.00%	**1:**	0	0.00%
2:	2	5.41%	**2:**	3	5.00%
3:	7	18.92%	**3:**	9	15.00%
4:	17	45.95%	**4:**	31	51.67%
5:	11	29.73%	**5:**	17	28.33%

Table 7.10: Descriptive statistics for stakeholder understanding (survey 3).

Run for survey 3 (*Figure 7.17*, *Table 7.10*), there were again no statistically significant differences between those students who used the CCMT and those who did not; $U = 1130.5$, $z = 0.165$, and $p = 0.869$. This is reinforced by the results to a related question about the value of the CCMT (*Figure 7.18*, *Table 7.11*): "To what degree has the constraint matrix impacted you or your group's understanding of the stakeholders relevant to this project?" This question was only asked to the experimental population who actually used the tool, and responses were again rated on a 1-5 Likert scale ranging from "no impact" to "large impact." The student responses to the perceived impact of the CCMT were distributed relatively evenly around the "neutral" response, and there was no significant difference between the two times this question was asked (on survey 2 and survey 3); $z = 1.847$, $p = 0.065$, and there were $N = 23$ positive differences, $N = 15$ negative differences, and $N = 22$ ties between the surveys.

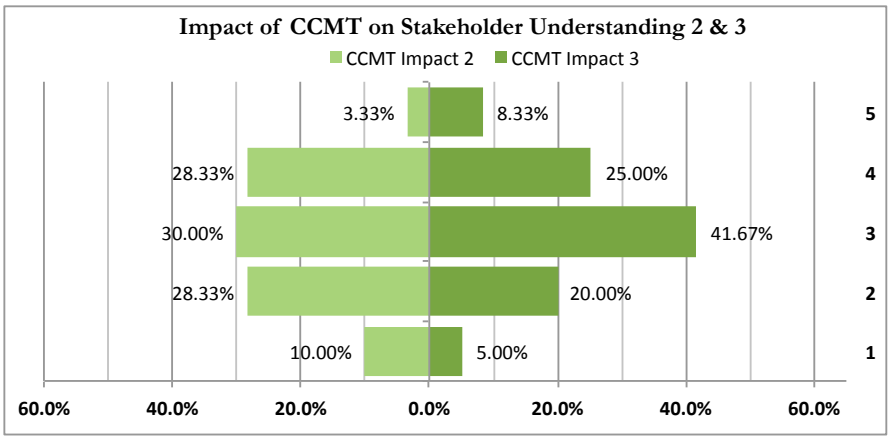
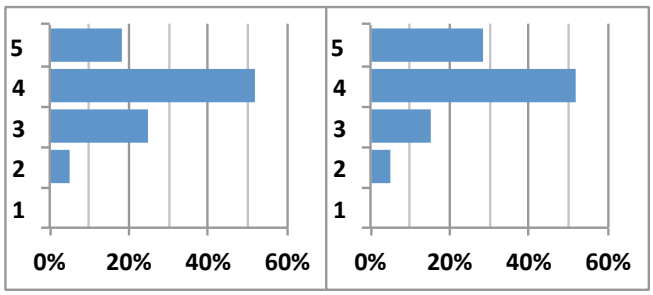


Figure 7.18: Frequency sorted responses for CCMT impact on stakeholder understanding (survey 2 and 3).

CCMT Impact 2			CCMT Impact 3		
Min:	1		**Min:**	1	
Max:	5		**Max:**	5	
Median:	3		**Median:**	3	
Mode:	3		**Mode:**	3	
Mean:	2.867		**Mean:**	3.117	
Quartile 1:	2		**Quartile 1:**	2.75	
Quartile 3:	4		**Quartile 3:**	4	
IQR:	2		**IQR:**	1.25	
Frequency sorted responses			**Frequency sorted responses**		
1:	6	10.00%	**1:**	3	5.00%
2:	17	28.33%	**2:**	12	20.00%
3:	18	30.00%	**3:**	25	41.67%
4:	17	28.33%	**4:**	15	25.00%
5:	2	3.33%	**5:**	5	8.33%

Table 7.11: Descriptive statistics for CCMT impact on stakeholder understanding (survey 2 and 3).

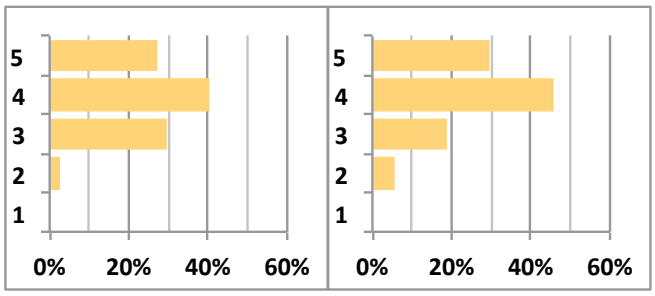
In order to assess if the students attitudes changed over time within each population, a Wilcoxon Signed-Rank test was run for each independent group to determine if the distribution was the same across both surveys. Running the test for the experimental population (*Figure 7.19*) did not yield a statistically significant change in 'stakeholder understanding' between the two surveys; $z = 1.577$, $p = 0.115$. There were $N = 23$ positive differences, $N = 14$ negative differences, and $N = 23$ ties between the surveys.



Experimental Survey 2		Survey 3	
Median:	4	**Median:**	4
Mode:	4	**Mode:**	4
Mean:	3.833	**Mean:**	4.033
Quartile 1:	3	**Quartile 1:**	4
Quartile 3:	4	**Quartile 3:**	5
IQR:	1	**IQR:**	1

Figure 7.19: Comparing frequency sorted responses and descriptive statistics for stakeholder understanding (experimental).

Running the Wilcoxon Signed-Rank test again for the control population (*Figure 7.20*) also reveals no statistically significant change; $z = 0.379$, $p = 0.704$. There were $N = 13$ positive differences, $N = 10$ negative differences, and $N = 14$ ties between the surveys.



Control Survey 2		Survey 3	
Median:	4	**Median:**	4
Mode:	4	**Mode:**	4
Mean:	3.919	**Mean:**	4.000
Quartile 1:	3	**Quartile 1:**	4
Quartile 3:	5	**Quartile 3:**	5
IQR:	2	**IQR:**	1

Figure 7.20: Comparing frequency sorted responses and descriptive statistics for stakeholder understanding (control).

Throughout the course of the study there was little difference between the population who used the CCMT and the population that did not with regard to the students' perceived

understanding of relevant stakeholders. This is supported by the feedback given by CCMT users whose responses, as a whole, were relatively indifferent and centered around the neutral response. This may also have been largely due to the fact that many students contrasted the effect of the CCMT on stakeholder understanding with their actual *in situ* observation. While the tool is intended to increase awareness of stakeholder perspective, it is in no way intended as a substitute for the detailed understanding gained from user research. This assumption is rooted in informal interactions with the students, as well as the open-ended feedback gathered from the student surveys. One student noted, "most of the information in the matrix (and thus any understanding it provided) was derived from our shadowing and interview experiences. While it helped show how different stakeholders interacted, the interviews themselves were much more illuminating of the stakeholders' issues." There were a number of responses that conveyed a similar position.

7.3.6 Understanding of Relevant Factors

In order to assess the effects of the CCMT on students' understanding of a design's relevant factors, students in both populations were asked to rate their confidence that their group had "…explored all of the factors and constraints that [were] relevant to [their] design problem." Responses were recorded using a Likert scale ranging from 1-5, with 1 representing "very limited many factors left unaddressed" and 5 being "all factors addressed." This question only appeared on survey 3.

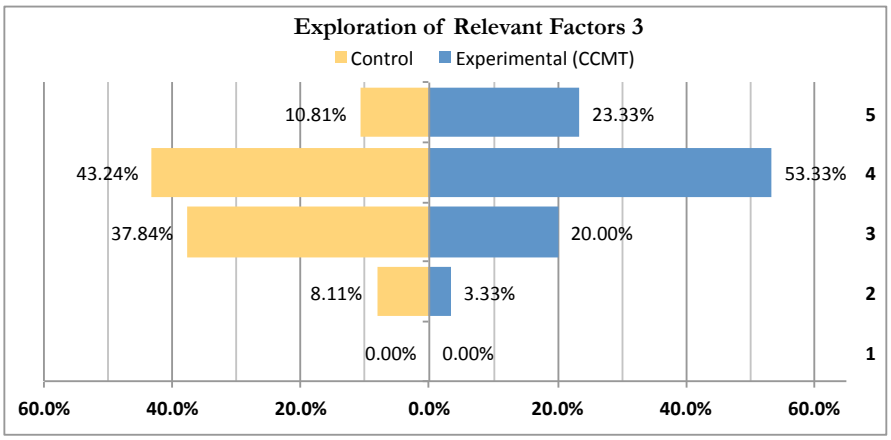


Figure 7.21: Frequency sorted responses for understanding of relevant factors (survey 3).

	Control		Experimental (CCMT)	
Min:	2		**Min:**	2
Max:	5		**Max:**	5
Median:	4		**Median:**	4
Mode:	4		**Mode:**	4
Mean:	3.568		**Mean:**	3.967
Quartile 1:	3		**Quartile 1:**	4
Quartile 3:	4		**Quartile 3:**	4
IQR:	1		**IQR:**	0
Frequency sorted responses			**Frequency sorted responses**	
1:	0	0.00%	**1:**	0	0.00%
2:	3	8.11%	**2:**	2	3.33%
3:	14	37.84%	**3:**	12	20.00%
4:	16	43.24%	**4:**	32	53.33%
5:	4	10.81%	**5:**	14	23.33%

Table 7.12: Descriptive statistics for understanding of relevant factors (survey 3).

To compare the distributions between populations, a Mann-Whitney U test was run to determine if there were differences in the students' perceived exploration and understanding of the factors relevant to their design problem between individuals who used the CCMT and those who did not (*Figure 7.21*, *Table 7.12*). The respondents' attitudes differed in a statistically significant way between the control and the experimental population; $U = 1413$, $z = 2.436$, and $p = 0.015$.

This is supported by the fact that the experimental population felt that the CCMT had a positive impact on their understanding of the design problem and its relevant factors (*Figure 7.22*). The responses of the students in the experimental population reveal a statistically significant increase in the perceived impact of the CCMT on their understanding of the factors

relevant to the design problem between surveys given in the middle and at the end of the project (Wilcoxon Signed-Rank test; $z = 2.442$, $p = 0.015$ with $N = 29$ positive differences, $N = 11$ negative differences, and $N = 20$ ties between the surveys). By the conclusion of the project, 55% (responded with a 4 or 5) of students felt that the CCMT positively impacted their understanding of relevant factors, 23.33% gave the neutral response of 3, and 21.67% of respondents answered with a score of 2. Zero respondents responded with a score of 1, which represented that the CCMT had "no impact" on their understanding of the relevant factors.

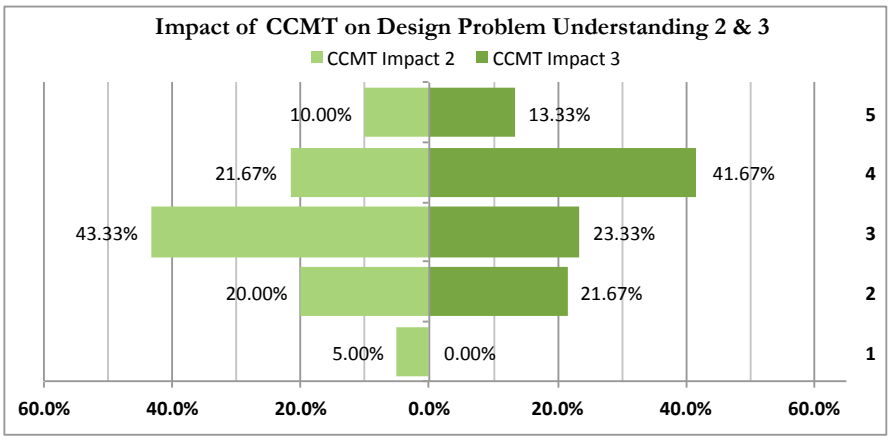


Figure 7.22: Frequency sorted responses for CCMT impact on problem understanding (survey 2 and 3).

CCMT Impact 2		
Min:	1	
Max:	5	
Median:	3	
Mode:	3	
Mean:	3.117	
Quartile 1:	2.75	
Quartile 3:	4	
IQR:	1.25	
Frequency sorted responses		
1:	3	5.00%
2:	12	20.00%
3:	26	43.33%
4:	13	21.67%
5:	6	10.00%

CCMT Impact 3		
Min:	2	
Max:	5	
Median:	4	
Mode:	4	
Mean:	3.467	
Quartile 1:	3	
Quartile 3:	4	
IQR:	1	
Frequency sorted responses		
1:	0	0.00%
2:	13	21.67%
3:	14	23.33%
4:	25	41.67%
5:	8	13.33%

Table 7.13: Descriptive statistics for CCMT impact on problem understanding (survey 2 and 3).

At the conclusion of the study, the students who had used the CCMT felt that they had more thoroughly considered all of the factors relevant to their particular design problems. In

conjunction with the mostly positive responses about the CCMT's impact along this dimension, it indicates that the CCMT encouraged students to explore a wider variety of factors in a more deliberate and considered way. This is one of the intended effects of the tool and was informally confirmed through interactions with the students, as well as through many of their open-ended responses. One student noted the CCMT's role in identifying previously unrecognized constraints, saying, "It made us think about some contraints [sic] that we did not think about at first. This made the group go back and create new features to over come these contraints [sic]." Another student noted how populating the matrix led to considerable design changes, stating, "We took quite a bit of time to go through the constraint matrix and specifically fill out all we could and take the time to think about how each constraint applies to which to see how each change affects which. We ended up filling out a matrix twice because our design changed considerably and filling out the matrix the first time helped us to understand that we needed to change our design around a lot."

7.3.7 CCMT Impacts

On surveys 2 and 3, efforts were made to assess the impact of the CCMT on three factors related to the design process. These factors were: the students' perceived understanding of the design problem, their understanding of relevant stakeholders, and the impact of the tool on their ideation process. These survey items were only presented to the experimental section, as these were the only students who used the tool. All responses were recorded using a Likert scale ranging from 1-5, with 1 representing "no impact" and 5 being "large impact."

The impact of the CCMT on 'stakeholder understanding' was previously covered in *Section 7.3.5*. The distribution of student responses was centered around the median response value, and revealed no change in the tool's impact on stakeholder understanding over the course of the project. In student responses, the CCMT was frequently contrasted with the other user-centered research techniques employed during the course of the project, which were noted to be more helpful for building an understanding of the relevant stakeholders. The impact of the CCMT on 'design problem understanding' was covered in *Section 7.3.6*, and revealed a statistically significant increase over the course of the project. Responses initially were centered around the median response value, but skewed toward the positive by the conclusion of the project. For

survey three, the majority of respondents rated the impact of the CCMT on their understanding of their design problem as a '4' or '5.'

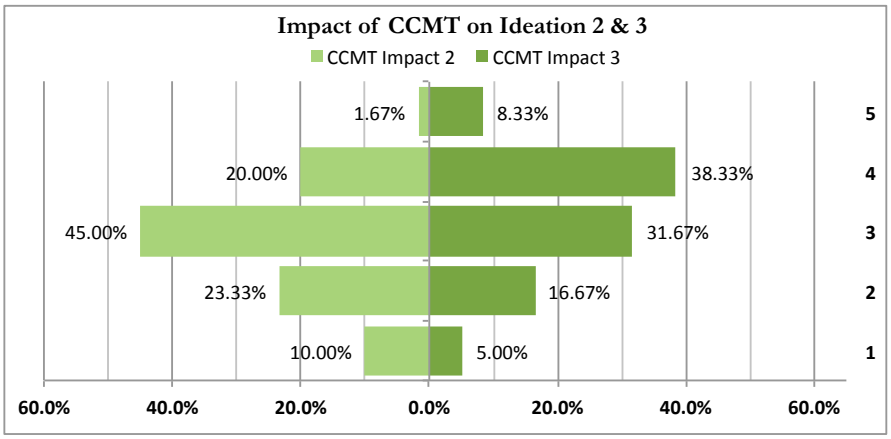


Figure 7.23: Frequency sorted responses for CCMT impact on ideation (survey 2 and 3).

CCMT Impact 2	
Min:	1
Max:	5
Median:	3
Mode:	3
Mean:	2.800
Quartile 1:	2
Quartile 3:	3
IQR:	1

Frequency sorted responses		
1:	6	10.00%
2:	14	23.33%
3:	27	45.00%
4:	12	20.00%
5:	1	1.67%

CCMT Impact 3	
Min:	1
Max:	5
Median:	3
Mode:	4
Mean:	3.283
Quartile 1:	3
Quartile 3:	4
IQR:	1

Frequency sorted responses		
1:	3	5.00%
2:	10	16.67%
3:	19	31.67%
4:	23	38.33%
5:	5	8.33%

Table 7.14: Descriptive statistics for CCMT impact on ideation (survey 2 and 3).

The CCMT's impact on student ideation has not been covered to this point, but offers results similar to the tool's impact on design problem understanding (*Figure 7.23*, *Table 7.14*). When asked the question, "to what degree has the constraint matrix impacted your ideation or design solutions?" Student responses began roughly evenly distributed around the median response, and were even slightly skewed towards the "no impact" response—33.33% of responses for '1' and '2', versus 21.67% responses for '4' and '5'. As students moved towards the conclusion of the project the distribution of responses for the 'impact of the CCMT on ideation'

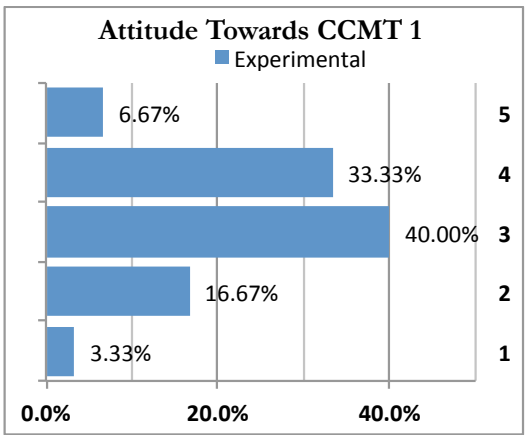
moved positively in a statistically significant way; $z = 3.738$, $p = < 0.005$ with $N = 28$ positive differences, $N = 5$ negative differences, and $N = 27$ ties between the surveys (Wilcoxon Signed-Rank test).

Looking at the open-ended student responses, there were certainly those who felt the tool had no impact on their ideation or the development of design concepts. One student noted, "We did not get any major design ideas or revelations with our matrix, and it did nothing to generate ideas or change concerns with the constraints." But there were a number of others who noted the effectiveness of the tool in helping the group to direct their focus and encourage exploration. One individual stated that, "it made us think in a more broad sense. Not just think of one solution and expand on it. We were able to think of many different solutions or ideations and then lower them down to just a couple by using the design matrix." Another pointed out that, "the constraint matrix helped focus us to a productive line of development earlier in the process." And another still noted that, "I think it helped out to establish these stakeholders. The [CCMT] basically brokedown [sic] your thinking to inspire ideas."

Looking at the three questions specifically designed to assess the CCMT's impact on the students' processes revealed that the tool had a significantly positive impact on the group's ability to understand the design problem, and aided in their efforts to actually develop solutions to the problem. The students were less certain about the value of the tool with regard to helping them develop an understanding of the relevant stakeholders; this attitude did not change over the course of the project.

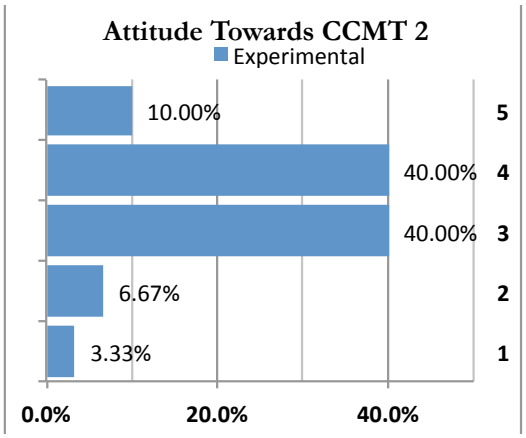
7.3.8 Attitude toward the CCMT and Future Use

Throughout the duration of the project, and on each of the three surveys, the experimental population was asked to rate their attitude toward the CCMT. Their attitudes were again assessed on a Likert scale item with responses ranging from 1, "most negative" to 5, "most positive."



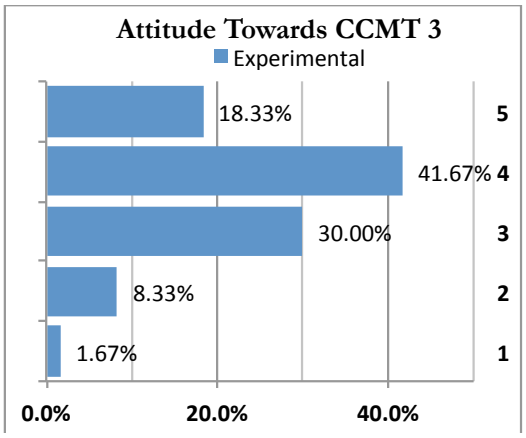
Frequency sorted responses		
1:	2	3.33%
2:	10	16.67%
3:	24	40.00%
4:	20	33.33%
5:	4	6.67%
Median:	3	
Mode:	3	
Mean:	3.233	
Quartile 1:	3	
Quartile 3:	4	
IQR:	1	

Figure 7.24: Frequency sorted responses and descriptive statistics for students' attitudes towards CCMT (survey 1).



Frequency sorted responses		
1:	2	3.33%
2:	4	6.67%
3:	24	40.00%
4:	24	40.00%
5:	6	10.00%
Median:	3.5	
Mode:	4	
Mean:	3.467	
Quartile 1:	3	
Quartile 3:	4	
IQR:	1	

Figure 7.25: Frequency sorted responses and descriptive statistics for students' attitudes towards CCMT (survey 2).



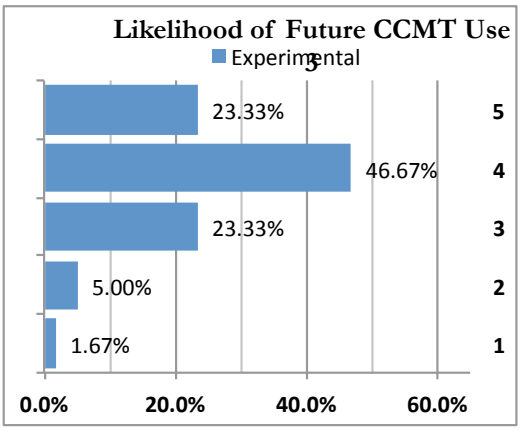
Frequency sorted responses		
1:	1	1.67%
2:	5	8.33%
3:	18	30.00%
4:	25	41.67%
5:	11	18.33%
Median:	4	
Mode:	4	
Mean:	3.667	
Quartile 1:	3	
Quartile 3:	4	
IQR:	1	

Figure 7.26: Frequency sorted responses and descriptive statistics for students' attitudes towards CCMT (survey 3).

Looking at the frequency sorted bar charts (*Figures 7.24, 7.25, 7.26*) and the descriptive statistics, it appears that the students' attitudes were neutral at the beginning of the project—which makes sense, as they had yet to use the tool. As the project progressed and their use of the tool increased, attitudes toward the tool became increasingly positive. The tail of the distribution over the '1' and '2' responses steadily shrank, and the whole distribution appears to pull upwards toward the more positive responses. But visual analysis is not enough, and a Friedman test was run to determine if the distributions changed across the three surveys. The results reveal that there was a statistically significant change; $\chi^2(2) = 13.031$, $p = 0.001$. Thus we accept that the distributions for the experimental population changed significantly over the course of the project.

In order to assess where these differences occurred, multiple comparisons using the Wilcoxon Signed-Rank were performed. The Wilcoxon Signed-Rank test did not yield a statistically significant increase for 'attitude towards the CCMT' between the beginning (survey 1) and middle (survey 2) of the project, $z = 1.608$, $p = 0.108$. Running the test again between the middle (survey 2) and end of the project (survey 3), showed a statistically significant increase; $z = 2.058$, $p = 0.040$. Comparing survey 1 and 3, also yielded a statistically significant increase with a higher degree of confidence; $z = 2.693$, $p = 0.007$.

At the conclusion of the project, students were also asked to rate "…how likely [they] would be to use the constraint matrix again" on a scale ranging from 1, "very unlikely" to 5, "highly likely." While statistical tests are largely irrelevant for a question asked once to a single test population, we can still gain some insight from looking at their responses (*Figure 7.27*). The responses were overwhelmingly positive, with 70% of responses falling in the 4-5 range. This indicates that 70% of the students would be likely to use the tool again. This is in stark contrast to only 6.67% of responses falling in the 1-2 range. The remaining 23.33% of the students provided the neutral response (3) indicating that they were uncertain if they would consider using the tool again.



Frequency sorted responses		
1:	1	1.67%
2:	3	5.00%
3:	14	23.33%
4:	28	46.67%
5:	14	23.33%
Median:	4	
Mode:	4	
Mean:	3.850	
Quartile 1:	3	
Quartile 3:	4	
IQR:	1	

Figure 7.27: Frequency sorted responses and descriptive statistics for likelihood of future use (survey 3).

Students were also asked to explain their answer, and provide information with regard to the circumstances in which they would be likely to use the tool. To provide a point of reference the examples of "school project, industry, more complex, less complex, etc." were provided. While it is possible that these examples may have biased the students' responses toward particular circumstances, some examples were necessary in order to provide context for the question. In order to more accurately aggregate this information, categories were created in order to capture the overall themes of the responses (*Figure 7.28*); each of the open-ended student responses was included in one or more of these categories. This clustering analysis was done in order to identify patterns in the qualitative data. In order to reduce the subjectivity and influence of the researchers, the task of defining categories and sorting responses was completed by an impartial observer (the original formulation and sort can be seen in *Appendix K*).

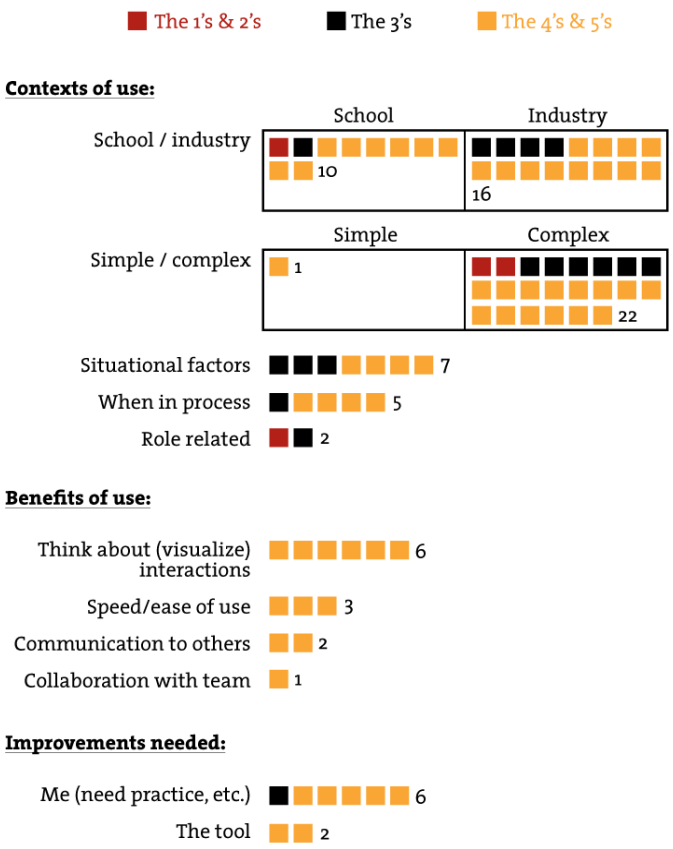


Figure 7.28: Clustering analysis for students written responses about CCMT reuse.

The individual responsible for the sort broke the responses down into three basic categories: contexts of use, benefits of use, and improvements needed. Those categories were populated with color coded marks indicating the student's response on the 1 to 5 scale. Within the 'contexts of use' students identified a number of contexts in which they would potentially leverage the CCMT, ranging from capstone projects and master's work to industry projects and project management settings. One student noted, "I intend to try using it again the next time I attempt to design a project. Looking back on past things I've made and designed I can imagine several problems I may have been able to anticipate had I had access to a similar tool." Of the sixty respondents ten *specifically* envisioned usefulness in future academic endeavors: "I can see using this for my capstone project maybe other larger scale open school project." Another referenced his intention to use the CCMT as he continued to develop the concept arrived at for this project, saying, "It would be one of my top priorities to work on the constraint matrix. It

will give me the exact idea about all the constraints, be it physical, market, cultural, etc…. As of now, I am planning to work more on my current product design and improve it further… to combine all the ideas in the best possible way. It could be used in all kinds of projects."

Conversely, there were 16 students who referenced the CCMTs potential value in an industry setting: "Probably in the industry, and most likely when working with several projects. As a project manager you want to see which constraints yo up [sic, you] have overall and for each project. Also, since the matrix include [sic] the stakeholders, it proves to be a great tool when dealing with a lot of connected information." Another student noted, "I would consider the matrix for very complex designs and probably very integrated architecture. For school projects, I would likely not find the need for it, [but] Industry might present more situations conducive to its use." One student referenced his experience in industry by saying, "I would use the tool in a situation where I have to create something from scratch or near scratch. I work during summers in an R&D department, and such a tool fits in perfectly with the work we do there."

While there were opinions favoring both academia and industry settings, there was no such division when it came to the tool's perceived usefulness in simple versus complex projects. Of the sixty respondents, twenty-two noted that the tool would be more useful for more complex design projects. Only one student thought the tool would be useful for design projects simpler than the conducted class project. The general tone of many of the responses is captured by this comment: "In a more complex situation I think it would be very helpful to have something breaking up and organizing the way its different constraints are interacting." But others went into greater detail, noting the value of the tool for tracking change, "I think this would be helpful in developing very complex systems so you can see how a change in some functionality can effect [sic] the rest of the system;" and its value for helping to balance constraint trade-offs, "I would use the constraint matrix if there were more multiple important constraints which worked against one another and at the same time, pulled the product design in very different directions (such as can happen with a complex design and user base)."

The students also referenced other situational, process-related, and role-related factors as part of the context which would encourage future use of the CCMT. Beyond these specifically referenced contexts, a few students even noted that the tool would be potentially useful apart

from any sort of design context; for instance, "I think that the format is awesome. I think it could be applied to projects that aren't even design work."

While not specifically required, many of the students that would reuse the tool also cited potential benefits which provide justification for its use. Of the respondents, six referenced the role of the tool in helping them to think about and visualize the interactions that exist among constraints; "I would use the matrix for anything in the future that has multiple areas that can be altered by one another and that can be better visualized and understood by using the matrix. I would use it again because I do feel it is helpful… with how I used it for this course's project." Three students referenced the tool's ease of use, and two more specifically called out the value of the CCMT as a communication tool. And one student referenced the value of the tool to help facilitate collaboration within a team.

A few students also stated that they would potentially reuse the tool, but laid out some conditions—primarily, improvements in either the tool or their own practices. Two students called for improvements to the tool. One student expressed a desire to see each of the interaction rows summed in order to quickly assess each constraint. Another student echoed the need to sum interaction values, and further desired to track both positive and negative interactions (a capability that was not included in the first iteration of the tool), saying, "what would have made the matrix infinitely more helpful would have been if signs (+/-) could be assigned to the numbers. For example: carrying capacity and lightweight structure have a strong negative correlation, whereas mechanical advantage and ability to be operated by one person have a positive correlation. It would have been helpful to see this - not just how strong the correlation, but also whether it was helpful or a hindrance. Of course, the constraints would need to be phrased in such a way to make this possible. These values could then be summed to provide useful insight. It would be easy to assess whether adding a feature had a net positive impact or a net negative impact on the overall design."

Apart from changes to the tool, six students communicated that they would need to improve their own practices or knowledge prior to reusing the tool. These students referenced their own perspectives and understanding, which shows a need for greater experience with the tool, additional practice, or improved instruction: "It was extremely useful and I would use it again but I would first want to practice with it on smaller projects because… it is fairly tricky to fill in the essentials. But I would have a very likely chance of using it agian [sic]." Another

student commented, "I would be willing to use the constraint matrix again, but I would spend more time evaluating the correlations and values input to the matrix. I feel that this would provide much more value to the matrix as well as a better understanding of how to use the results of the matrix." Responses like these were also common in informal interactions between the researchers and the students. These comments highlight the need for improved tutorials and instruction on the CCMT's purposes, capabilities, and use. They also bring to light the fact that regardless of the instruction, experience with the tool is still necessary; there is no substitute for leveraging the tool in a real design process.

The numerical ratings and written responses to the questions about students' attitudes towards the matrix and potential reuse are encouraging. Despite difficulties related to the actual application of the tool and a less–than–ideal project structure, these results reveal a generally positive attitude toward the tool and its perceived future value. Students' opinions of the tool steadily improved throughout the project as they gained experience with the tool, and the majority of students felt that they would like to attempt using the tool again in the future—a number even expressed concrete plans for using it for personal projects, Master's work, or undergraduate capstone projects.

7.4 Data Analysis: Evaluator Results

After the conclusion of the student design projects, the design solutions were evaluated by a panel of experts who possess a range of academic and practical experience in both engineering and design. These twenty-six evaluators judged the student design projects over four dimensions: overall design quality, understanding of relevant factors, innovation potential, and creativity (the evaluator survey and complete responses can be seen in *Appendix H and Appendix I*). Additionally, the scores for each of these four dimensions were summed to provide a 'total score'. This section presents the results of the evaluator surveys for fifteen student projects: nine projects from the experimental section (groups who used the CCMT) and six control projects (who did not use the CCMT). The experimental sample consists of 234 evaluations (9 projects x 26 evaluators), and the control sample 156 (6 projects x 26 evaluators). Each survey question corresponds to one dimension, and is analyzed individually before attempting to draw more

general conclusions. Data is compared across test populations, and all statistical analyses account for the differences in sample size.

Before examining the data in detail, it is necessary to recognize the difficulty of design evaluation: in the absence of explicit quantitative measures, the evaluation of any design concept is inherently subjective. Every evaluation is dependent upon the background, experience, perspective, and preferences of the evaluator. Each evaluator uniquely imposes the set of criteria that shape their expectations and evaluations, and that set of criteria is based upon their own understanding of the design problem and external experience. Each evaluator implicitly defines a different set of criteria, and then prioritizes those criteria differently. In this way, design evaluation is similar to the act of design itself, with the imposition of evaluation criteria being very much akin to the designer's imposition of constraints. Just as individual designers can arrive at different solutions for the same design problem, so too can individual evaluators arrive at different conclusions for a single design. One evaluator may prioritize creativity, another execution, and another aesthetics. This is an obvious oversimplification, as in reality the evaluations are themselves a complex combination of factors. Each survey question (corresponding to a dimension of evaluation) is then open to a range of interpretations, but is intended to represent the evaluator's general assessment of a design. Overall design quality, for instance, is intended to capture the evaluator's assessment of overall 'fitness' with respect to a stated problem and context.

The evaluation process is further complicated by the fact that evaluators were not, in most instances, subject matter experts, and they were forced to evaluate the design solutions removed from the actual context of use. For instance, evaluators had to assess the design of a new IV pole, without having ever worked as a nurse or explored the problem in an actual hospital context. Additionally, the evaluations were based upon the previously discussed two-page design summaries, rather than any sort of interaction with the prototype itself. This was a necessary simplification in order to facilitate participation and evaluation, but also opened this part of the study to significant uncertainty.

At times there were issues with regard to the students' abilities to communicate their ideas in a written format with sufficient fidelity. This was mentioned in a number of the evaluator comments, as well as in personal communications. For a few of the more poorly structured two-page summaries, comments like the following were all too frequent: "Where is

the product? Written words are descriptive of the product and the problem being addressed, however without a physical prototype, it is very difficult to establish and respond to the design teams' intent and solution to the problem. It is hard to see how the product would be used, and therefore assess whether or not it would be useful in this context without seeing the product." The group referred to by this evaluator did not even include pictures of their prototype within the two-page summary. Thus there were times when the quality of work was not accurately reflected in the two-page summary. Ultimately, this lead to situations in which negative evaluations may have resulted from a poorly written summary rather than a poor design, just as well–written summaries may have masked design deficiencies or portrayed the design in a more positive light.

While design evaluation is an unavoidably subjective and imprecise activity, this analysis was prioritized in an attempt to assess the impact of the CCMT on student design outcomes, however tenuously. Just glancing at the expert evaluations of the design projects quickly reinforces this subjectivity as the evaluations for any single design are quite inconsistent. Almost every design had evaluators who rated it highly and evaluators who scored it negatively. Project number 14, for instance, best exemplifies this inconsistency. Across the twenty-six raters, total scores for this project (a sum of the four questions, each rated on a 1-5 scale) ranged from 4 (the lowest possible score) to 20 (the highest possible score). In fact, two reviewers gave this project a total score of 4, while three reviewers gave this project a perfect 20. This sort of variability is a product of the difficulties inherent in design evaluation. While project 14 was one of the most polarizing projects, similar variation can be seen across a majority of the fifteen projects.

Examining plots of the total scores for each project ranked in ascending order reveals a great variability for each project regardless of test population (*Figure 7.29*). If raters consistently scored a project one could expect to see a relatively flat line, or at least a line with a relatively small slope. Instead, each of the projects is characterized by a line which increases from left to right at a fairly steady rate. There is still variability among projects (some were better than others), which can be seen in the relative vertical position of each line (higher lines have a higher mean total score). At the same time, the variability of total scores is evident for each of the lines, as well as across the entire set of projects. This is evidenced by the overall trend of lines rising steadily from left to right.

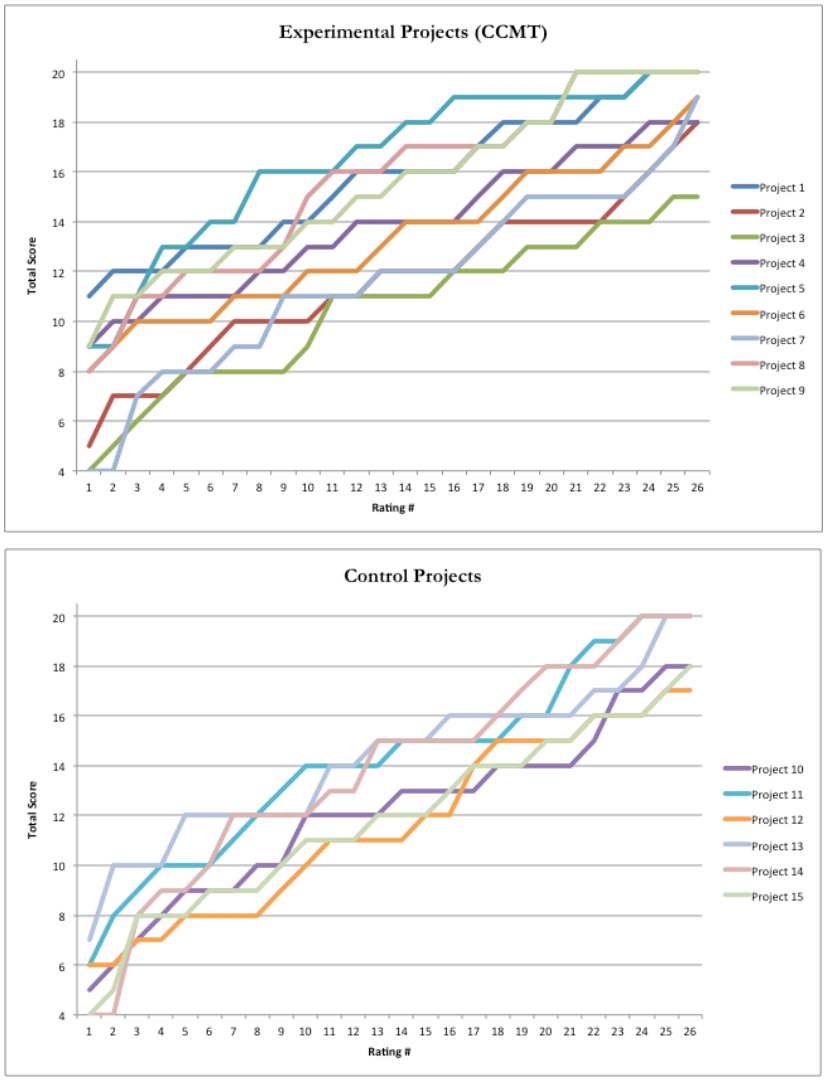


Figure 7.29: Project 'total scores' plotted in ascending order show little consistency across the 26 raters for either experimental or control populations.

Looking at the descriptive statistics for the evaluator rankings, the spread of evaluator total scores for each project ranged from 9 to 16 (the maximum possible spread), with an average spread of 12.33. Interquartile ranges for the fifteen projects ranged from 4 to 7, with an average IQR of 5.15. While standard deviation and coefficient of deviation are less than ideally suited to this data (because of its ordinal nature), they are included for descriptive purposes to further show the dispersion over the possible total score range (4 to 20). Standard deviations for the fifteen projects ranged from 2.71 to 4.46, and the average standard deviation across all of the

projects was 3.37. The coefficient of variation (CV) is a non-dimensional value that describes the dispersion of a variable. Because CV is unitless, the dispersion of a variable can be compared across variables in ways that standard deviations cannot (because standard deviation is dependent upon each variable's specific mean) [299]. The CV's for the 15 projects ranged from 17.59% to 32.33%, with an average of 25.56%.

Project #	MIN	MAX	SPREAD	IQR	MEAN	STD DEV	COEF DEV
1	11	20	9	5	15.73	2.77	17.59%
2	5	18	13	4	11.62	3.22	27.75%
3	4	15	11	5	10.50	3.05	29.09%
4	9	18	9	4.75	13.88	2.71	19.50%
5	9	20	11	4.5	16.50	3.24	19.62%
6	8	19	11	5	13.27	2.96	22.27%
7	4	19	15	6	11.65	3.72	31.92%
8	8	20	14	6	15.54	3.62	23.29%
9	9	20	11	5	15.46	3.30	21.32%
Experimental Average			11.56	5.03	13.79	3.18	23.60%
10	5	18	13	4.75	12.08	3.46	28.68%
11	6	20	14	4.75	14.15	3.79	26.77%
12	6	17	11	7	11.58	3.60	31.07%
13	7	20	13	4	14.23	3.12	21.90%
14	4	20	16	5.75	13.81	4.46	32.33%
15	4	18	14	5.75	11.81	3.58	30.36%
Control Average			13.50	5.33	12.94	3.67	28.52%
Average			12.33	5.15	13.45	3.37	25.56%

Table 7.15: Descriptive statistics that evidence the variability of the evaluator rankings.

While some variability in scores is to be expected across evaluators, it would be preferred if each project were judged more consistently across the 26 evaluators. In order to assess the consistency of measurements made by multiple observers measuring the same projects, the intraclass correlation (ICC) was determined. As each project was rated by the same twenty-six raters, it is possible to determine the reliability of a single judge as well as the reliability of the entire group of judges. The ICC(3,1) = 0.237 with a 95% confidence interval of [0.100, 0.402] indicates that any single rater should not be trusted (as they are relatively unreliable). But ICC(3,26) = 0.890 with a 95% CI of [0.742, 0.946] indicates relative reliability across the entire group of judges. While this exploration of the variability of raters was conducted for total score only, similar results can be seen for each of the four primary dimensions of evaluation. Ultimately, this indicates that despite the variability in the individual evaluations, there is still value in the set of evaluations as a whole.

While it is necessary to establish the reliability of the evaluators as a group across the complete population, further assessment of evaluator reliability provides additional insight. Determining intraclass correlation (ICC) independently for the experimental (projects 1-9) and control populations (projects 10-15) for the 'total project score' reveals a difference between the two populations: the ICC is noticeably lower for the control group (ICC(3,26) = 0.708) than the experimental group (ICC(3,26) = 0.928). This means that the evaluators judged the experimental projects more consistently (with less variation) than the control projects. ICCs were also calculated for teams 1-6 (ICC(3,26) = 0.941) and 4-9 (ICC(3,26) = 0.896) to ensure that the differences were not the result of sample size. This is further supported by the average coefficient of variation for the experimental (23.60%) and control (28.52%) populations.

Projects were also rank ordered by their standard deviation (*Table 7.16*), and the results are consistent with the ICC analysis: there is a pronounced difference between the standard deviations of the control projects and those of the experimental projects. Finally, Cliff's Delta was calculated for the two populations: Cliff's Delta = 0.59. Cliff's Delta is an effect size for ordinal data used to assess the statistical significance of differences between two groups. It is used to test equivalence of probabilities of scores in one group being larger than scores in another [300], [301]. The sample statistic is given by,

$$\hat{\delta} = \frac{\#(x_{i1} > x_{j2}) - \#(x_{i1} < x_{j2})}{n_1 n_2}$$

Where $\#(x_{i1} > x_{j2})$ is the number of comparisons between observations in the two groups for which the 'group 1' observation is larger than the 'group 2' observation.

Cliff's Delta has been argued as being more appropriate than *t*-tests or Cohen's *d* (two tests typically used to assess survey results), as the discrete, ordinal, and often non-parametric data that characterizes survey research frequently violates the assumptions of these tests. The 0.59 delta represents a large effect; delta > 0.147 is the typical criteria for statistical significance (similar to $p \leq 0.05$). For ease of analysis, the effect sizes of Cliff's Delta can be compared with the more widely used Cohen's *d*: "…a difference in means that represents a d effect size of 0.20 will have of delta value of 0.147, a d effect size of 0.50 corresponds to a delta value of 0.33, and a d effect size of 0.80 corresponds to a delta of 0.474" [302].

Project #:	Rater #: 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	SD	Exp.	Con.
14	9	17	12	18	12	9	12	18	4	20	8	15	15	20	15	19	13	18	12	10	13	20	15	16	15	4	4.55		x
11	15	18	11	14	12	15	14	16	20	14	13	6	14	20	19	19	9	10	16	10	15	15	8	15	10	20	3.86		x
7	7	11	15	16	12	4	15	11	8	12	8	19	12	8	11	12	15	15	17	11	9	14	4	15	13	9	3.79	x	
8	11	20	11	17	16	18	13	18	12	20	8	20	9	20	16	17	16	15	20	12	17	17	12	20	12	17	3.69	x	
12	16	15	12	11	15	7	8	8	7	15	14	11	6	16	8	6	17	15	12	9	10	16	17	11	11	8	3.67		x
15	16	14	8	17	16	5	15	13	12	16	11	11	9	8	8	15	14	9	4	9	18	10	11	14	12	12	3.66		x
10	15	12	8	14	13	7	6	10	12	18	13	9	10	12	17	13	14	18	12	9	14	17	5	14	9	13	3.53		x
9	13	17	12	20	13	12	16	17	12	18	14	20	9	20	20	15	14	16	15	13	18	20	16	20	11	11	3.36	x	
5	18	19	13	16	16	9	17	14	20	20	13	19	19	14	16	19	19	20	9	19	16	11	17	18	19	19	3.30	x	
2	17	11	12	18	14	5	7	13	10	12	12	8	10	14	10	15	14	12	9	14	11	7	7	10	16	14	3.29	x	
13	10	16	10	20	16	7	12	12	12	17	15	18	15	15	16	16	10	14	14	12	17	16	12	20	12	16	3.18		x
3	6	11	8	11	12	8	12	9	13	15	8	14	11	13	8	13	7	4	11	12	8	15	14	5	11	14	3.11	x	
6	10	16	10	15	12	10	9	11	11	16	14	10	12	16	12	14	13	17	17	16	18	11	14	19	14	8	3.01	x	
1	15	20	11	19	14	12	16	12	13	18	12	16	13	20	16	18	18	17	16	13	14	18	20	19	16	13	2.82	x	
4	14	14	11	18	17	13	12	17	16	18	9	17	10	14	10	14	12	11	18	14	16	15	13	16	11	11	2.76	x	

Table 7.16: Rank ordering standard deviations for project total score shows that groups who used the CCMT were evaluated with less variation.

So, how are we to interpret this data? Is there something about the experimental groups' use of the CCMT that allows them to convey information about their solutions in a way that better facilitates assessment? While it is not possible to state with a high degree of certainty, the higher correlation among raters for the experimental projects may be a result of the CCMT's ability to mirror the structure of the design problem, and act as a knowledge base. As the experimental groups were those that populated the CCMT, they may have had a more clear sense of their problems and their designs. By forcing the groups to explicitly list key constraints, and constraint weights, the matrix may have acted as something of an informal outline for their two-page summaries. Using their matrices as a starting point for the summary may have allowed experimental groups to better describe their projects in such a condensed format, by helping groups to generate a sense of what to discuss and how to prioritize that information. Conversely, control groups would have had to work backwards from their final prototypes in order to generate the two-page summaries.

When considered in light of the students' own contexts—projects were due near the end of the semester when students were simultaneously concerned with finishing this project, projects for other courses, final exams, graduating, etc.—the CCMT likely acted as a valuable starting point by providing a list of talking points that allowed the experimental groups to more thoroughly and concisely describe their projects. This hypothesis is supported by a student comment that highlights the role the CCMT can play in communicating information about the design and the group's design rationale: "If I were to try and explain a product to someone, I would definitely use this matrix. It's an excellent tool for that. Any 'why' question that they ask about the product can be pretty easily answered with this matrix. Example: Q: Why is it this size? A: Click on the size constraint and show how many other constraints helped drive the final size."

This potential ability to improve communication was previously unseen, but may certainly be a benefit of applying the CCMT within a real-world design process—allowing designers to quickly justify to higher ups, clients, or other teams their design decisions by talking through the underlying constraint relationships.

Still, because of the large number of complicating factors associated with design evaluation, it is necessary to exercise caution when drawing conclusions from this data. It is therefore necessary to include an understanding of these factors in any account of the data. Despite these difficulties, however, conducting these expert evaluations was necessary in order to *attempt* to assess the impact of the CCMT on the students' design outcomes. While this data cannot definitively show a correlation between the use of the CCMT and an increased quality of design outcome (or improved communication of the design concept), the results are included as one data point that is useful in building a more complete picture of the CCMT's value and potential benefits.

7.4.1 Overall Design Quality

In order to assess the effects of the CCMT on the quality of the design solution, evaluators were asked to rate "…the overall quality of the design solution." Responses were recorded using a Likert scale item ranging from 1-5, with 1 representing "very poor solution" and 5 being a "very good solution." This question is open to a range of interpretations, and the "quality" of any design solution may, as mentioned, imply different things to different evaluators based upon personal experience, education, etc. Thus this question was intended as an "overall" evaluation of each concept. Results are compared across populations.

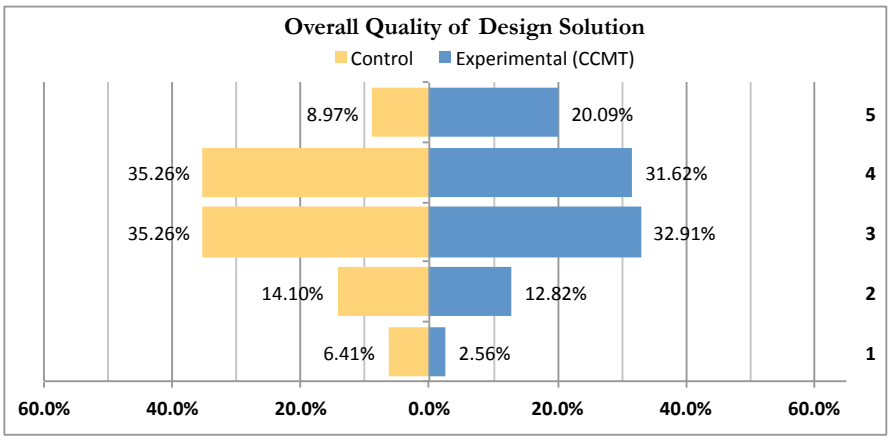


Figure 7.30: Frequency sorted responses for overall design quality.

	Control
Min:	1
Max:	5
Median:	3
Mode:	4
Mean:	3.2628
Quartile 1:	3
Quartile 3:	4
IQR:	1

Frequency sorted responses		
1:	10	6.41%
2:	22	14.10%
3:	55	35.26%
4:	55	35.26%
5:	14	8.97%

	Experimental (CCMT)
Min:	1
Max:	5
Median:	4
Mode:	3
Mean:	3.538
Quartile 1:	3
Quartile 3:	4
IQR:	1

Frequency sorted responses		
1:	6	2.56%
2:	30	12.82%
3:	77	32.91%
4:	74	31.62%
5:	47	20.09%

Table 7.17: Descriptive statistics for overall design quality.

To compare the distributions, a Mann-Whitney U test was run to determine if there were differences in overall solution quality between groups who used the CCMT and those who did not. The test revealed a statistically significant difference between the control and the experimental population; $U = 15786.5$, $z = -2.358$, and $p = 0.018$. Although the Mann-Whitney U test returns a statistically significant difference between the test populations, visual comparison shows data that *appears* to be quite similar. The largest difference between the two distributions is the increased frequency of 5 responses for the project groups who used the CCMT; on the low end, there is also a reduction in the number of 1s for the experimental population.

7.4.2 *Relevant Factors*

The evaluators were also asked: "How well does this design recognize and addresses all of the factors that may be relevant to this design problem? That is, how well does the design deal with all of the factors that you can envision being relevant in this context?" Responses were recorded using a Likert scale item ranging from 1-5, with 1 corresponding to "addressed very few relevant aspects of the problem," and 5 representing that the solution "addressed most all of the aspects of the design problem." This question is intended to address the evaluator's perceptions of how well a given design solution addressed a holistic set of constraints. But 'perception' is a key word, and this question is limited by each evaluator's capacity to envision the nature of the design problem and context. Results are again compared across populations.

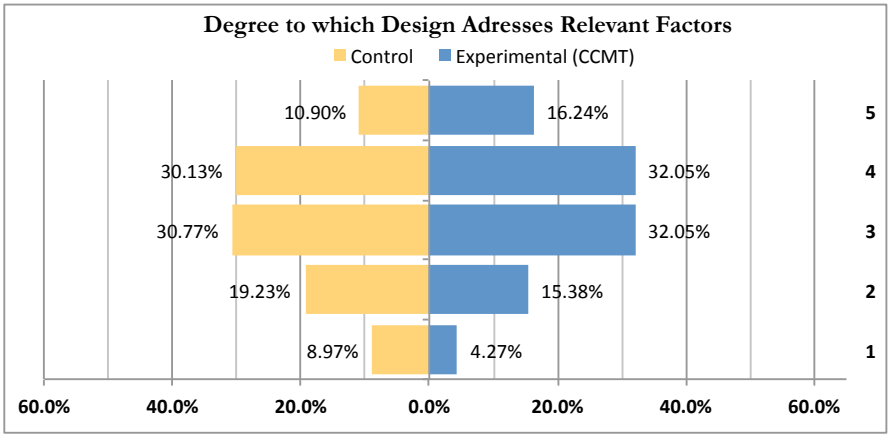


Figure 7.31: Frequency sorted responses for perception of the degree to which design addressed relevant factors.

	Control		Experimental (CCMT)	
Min:	1		1	
Max:	5		5	
Median:	3		3	
Mode:	3		3	
Mean:	3.147		3.406	
Quartile 1:	2		3	
Quartile 3:	4		4	
IQR:	2		1	
Frequency sorted responses				
1:	14	8.97%	10	4.27%
2:	30	19.23%	36	15.38%
3:	48	30.77%	75	32.05%
4:	47	30.13%	75	32.05%
5:	17	10.90%	38	16.24%

Table 7.18: Descriptive statistics for evaluator perception of the degree to which design addressed relevant factors.

To compare the distributions, a Mann-Whitney U test was run to determine if there were differences between populations in the students' ability to address all of the factors potentially relevant to a design problem. The test revealed a statistically significant difference between the groups who used the CCMT and those who did not; $U = 16022.5$, $z = -2.120$, and $p = 0.034$. Visual inspection of the bar charts and descriptive statistics reveals results that are slightly more positive for the experimental population (CCMT): Most notably with a greater number of 5s and a decreased number of 1s, and an inter-quartile range of 1 [3,4] as opposed to an IQR of 2 [2,4] for the control population. Still, the data *appears* quite similar despite a statistically significant difference shown by the Mann-Whitney U test. This is reinforced by the *p*-value of 0.034, which meets the significance level of 0.05, but is relatively high in comparison to many of the results seen in the student survey. It is also nearly double the significance value of the evaluation of overall design quality (0.018).

7.4.3 Innovation Potential

Evaluators were asked to rate "the innovation potential" of each design, in order to assess each group's ability to identify a novel design direction. In order to further clarify the intention of this question, evaluators were also asked, "Is the given solution novel, useful, and non-obvious?" (which are the three criteria required for receiving a U.S. patent). Because student solutions existed as design concepts, rather than fully developed design solutions, the question was further specified by asking, "If the design was further developed would it represent an innovation?" Again there are limitations to this question—chiefly, the evaluators' knowledge of current design solutions—but it was intended to assess the groups' ability to move beyond derivative problem formulations, obvious solutions, and simple fixes. Responses were rated on a Likert scale of 1 to 5, with 1 corresponding to "not innovative at all; a very derivative solution," and 5 standing for a solution that was "highly innovative within the given context."

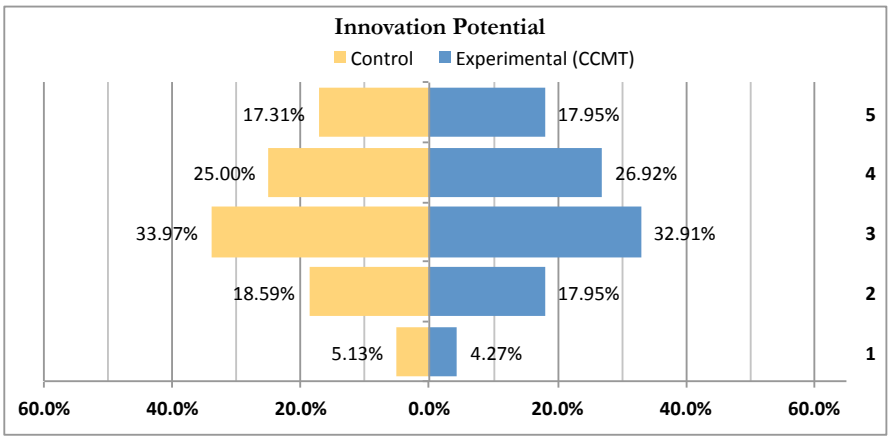


Figure 7.32: Frequency sorted responses for innovation potential.

	Control		Experimental (CCMT)	
Min:	1		1	
Max:	5		5	
Median:	3		3	
Mode:	3		3	
Mean:	3.308		3.363	
Quartile 1:	3		3	
Quartile 3:	4		4	
IQR:	1		1	
Frequency sorted responses			**Frequency sorted responses**	
1:	8	5.13%	**1:**	10	4.27%
2:	29	18.59%	**2:**	42	17.95%
3:	53	33.97%	**3:**	77	32.91%
4:	39	25.00%	**4:**	63	26.92%
5:	27	17.31%	**5:**	42	17.95%

Table 7.19: Descriptive statistics for innovation potential.

A Mann-Whitney U test was run to determine if there were differences between populations with regard to innovation potential. The test revealed no statistically significant difference between the groups who used the CCMT and those who did not; $U = 17746$, $z = -0.480$, and $p = 0.631$ (for a given significance level of 0.05). Visual inspection of the bar charts and descriptive statistics reveals two data sets that are similar in every way.

7.4.4 Creativity

In order to assess the effects of the CCMT on group creativity, evaluators were asked to rate "…the creativity exhibited in [each] design solution." Responses were recorded using a

Likert scale item ranging from 1-5, with 1 representing "little creativity exhibited" and 5 being a "highly creative solution." Once again, the evaluators' perceptions of creativity must be addressed, as creativity may mean entirely different things to two evaluators. An engineer and an industrial designer, for instance, may have entirely different perceptions about what represents a 'creative' solution.

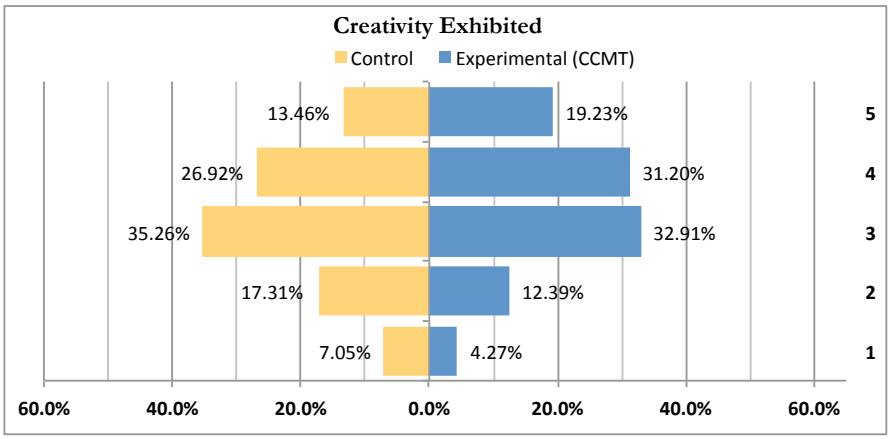


Figure 7.33: Frequency sorted responses for creativity exhibited in design solution.

	Control		Experimental (CCMT)	
Min:	1		1	
Max:	5		5	
Median:	3		4	
Mode:	3		3	
Mean:	3.224		3.487	
Quartile 1:	3		3	
Quartile 3:	4		4	
IQR:	1		1	
Frequency sorted responses			**Frequency sorted responses**	
1:	11	7.05%	**1:**	10	4.27%
2:	27	17.31%	**2:**	29	12.39%
3:	55	35.26%	**3:**	77	32.91%
4:	42	26.92%	**4:**	73	31.20%
5:	21	13.46%	**5:**	45	19.23%

Table 7.20: Descriptive statistics for creativity exhibited in design solution.

Comparing the distributions using a Mann-Whitney U test revealed a statistically significant difference between the control and the experimental populations; $U = 15825.5$, $z = -2.310$, and $p = 0.021$. Despite the similarities of the two distributions, visually inspecting the bar chart appears to show an experimental population (CCMT) that is skewed slightly more positive

than the control population. This is supported by the difference in medians between the two populations: 3 for the control population, and 4 for the experimental.

7.4.5 Evaluator Total Score

In order to gain a more complete picture of how the CCMT impacted student design results, the four evaluator scores for each group were combined to provide a single total score. These scores were once again evaluated between the two independent test populations. As each of the four evaluator questions were evaluated on a 1-5 scale, these total scores fall on a potential range of 4-20. The data is presented below, and implications are discussed.

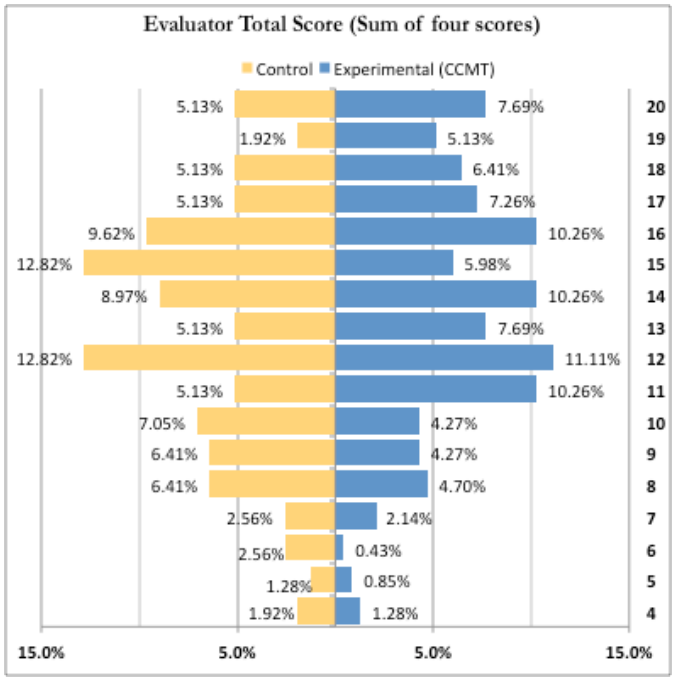


Figure 7.34: Frequency sorted responses for evaluator total score.

	Control		Experimental (CCMT)	
Min:	4		**Min:**	4
Max:	20		**Max:**	20
Median:	13		**Median:**	14
Mode:	15		**Mode:**	12
Mean:	12.942		**Mean:**	13.795
Quartile 1:	10		**Quartile 1:**	11
Quartile 3:	16		**Quartile 3:**	17
IQR:	6		**IQR:**	6
Frequency sorted responses			**Frequency sorted responses**	
4:	3	1.92%	**4:**	3	1.28%
5:	2	1.28%	**5:**	2	0.85%
6:	4	2.56%	**6:**	1	0.43%
7:	4	2.56%	**7:**	5	2.14%
8:	10	6.41%	**8:**	11	4.70%
9:	10	6.41%	**9:**	10	4.27%
10:	11	7.05%	**10:**	10	4.27%
11:	8	5.13%	**11:**	24	10.26%
12:	20	12.82%	**12:**	26	11.11%
13:	8	5.13%	**13:**	18	7.69%
14:	14	8.97%	**14:**	24	10.26%
15:	20	12.82%	**15:**	14	5.98%
16:	15	9.62%	**16:**	24	10.26%
17:	8	5.13%	**17:**	17	7.26%
18:	8	5.13%	**18:**	15	6.41%
19:	3	1.92%	**19:**	12	5.13%
20:	8	5.13%	**20:**	18	7.69%

Table 7.21: Descriptive statistics for evaluator total score.

Comparing the score distributions using a Mann-Whitney U test reveals a statistically significant difference between the control and the experimental populations; $U = 16104.5$, $z = -1.975$, and $p = 0.048$. Despite the similarities of the two distributions, visually inspecting the bar chart appears to show an experimental population (CCMT) that is skewed slightly more positive than the control population. This is supported by the slightly higher median and IQR for the experimental population. Still, statistical significance is achieved by the slimmest of margins—0.048 for a given significance level of 0.05.

The evaluator total score analysis, similar to the set of previous questions, seems to suggest a slight benefit to those student groups who employed the CCMT in their design processes. Of the four evaluator scores that showed a statistically significant difference (quality, relevant factors, creativity, and total score), overall design quality possessed the largest clearance with respect to the given significance level of 0.05 (0.018). Creativity and understanding of relevant factors followed with significance values of 0.021 and 0.034, respectively. At the same time, these scores show relatively tight significance values in comparison to the results seen in the student surveys. The notion that using the CCMT may improve the student design outcomes is supported by rank ordering the projects according to mean total project score (*Table 7.22*), and

calculating Cliff's Delta (discussed near the beginning of this section). In this instance Cliff's Delta = 0.22 represents a small to medium effect, and is greater than the significance criteria of 0.147.

	Rater #:																											
Project #:	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**mean**	**Exp.**	**Con.**
5	18	19	13	16	16	9	17	14	20	20	13	19	19	14	16	19	19	20	9	19	16	11	17	18	19	19	16.50	x	
1	15	20	11	19	14	12	16	12	13	18	12	16	13	20	16	18	18	17	16	13	14	18	20	19	16	13	15.73	x	
8	11	20	11	17	16	18	13	18	12	20	8	20	9	20	16	17	16	15	20	12	17	17	12	20	12	17	15.54	x	
9	13	17	12	20	13	12	16	17	12	18	14	20	9	20	20	15	14	16	15	13	18	20	16	20	11	11	15.46	x	
13	10	16	10	20	16	7	12	12	12	17	15	18	15	15	16	16	10	14	14	12	17	16	12	20	12	16	14.23		x
11	15	18	11	14	12	15	14	16	20	14	13	6	14	20	19	19	9	10	16	10	15	15	8	15	10	20	14.15		x
4	14	14	11	18	17	13	12	17	16	18	9	17	10	14	10	14	12	11	18	14	16	15	13	16	11	11	13.88	x	
14	9	17	12	18	12	9	12	18	4	20	8	15	15	20	15	19	13	18	12	10	13	20	15	16	15	4	13.81		x
6	10	16	10	15	12	10	9	11	11	16	14	10	12	16	12	14	13	17	17	16	18	11	14	19	14	8	13.27	x	
10	15	12	8	14	13	7	6	10	12	18	13	9	10	12	17	13	14	18	12	9	14	17	5	14	9	13	12.08		x
15	16	14	8	17	16	5	15	13	12	16	11	11	9	8	8	15	14	9	4	9	18	10	11	14	12	12	11.81		x
7	7	11	15	16	12	4	15	11	8	12	8	19	12	8	11	12	15	15	17	11	9	14	4	15	13	9	11.65	x	
2	17	11	12	18	14	5	7	13	10	12	12	8	10	14	10	15	14	12	9	14	11	7	7	10	16	14	11.62	x	
12	16	15	12	11	15	7	8	8	7	15	14	11	6	16	8	6	17	15	12	9	10	16	17	11	11	8	11.58		x
3	6	11	8	11	12	8	12	9	13	15	8	14	11	13	8	13	7	4	11	12	8	15	14	5	11	14	10.50	x	

Table 7.22: Rank ordering projects based upon means of total project score.

Based upon these results, in combination with the format of evaluation and the more general difficulties of design evaluation, it is difficult to draw meaningful conclusions about the tool's actual effect on the groups' design outcomes. But this data is not intended to justify the CCMT's value in and of itself. Instead, this is just one more set of data that *can* be used in combination with other results. When viewed as part of this larger collection of data, this helps to paint a more complete picture of the CCMT. It supports the CCMT's value within the context of student design activity, and helps to justify future work to continue assessing the tool's impact on processes and outcomes.

7.5 Conclusions from Initial Research Study

The following three tables represent a summary of the data and statistical results assessing the value of the CCMT within an academic engineering design educational context. Significance values are included. The first table is a summary of the data compared between independent samples: those who used the CCMT and those who did not. It reveals that by the conclusion of the project (survey 3) the only questions for which there was not a statistically significant difference between populations were the students' attitudes towards the design project and their understanding of the relevant stakeholders. In contrast, there were statistically significant differences for their attitudes towards teamwork, their shared understanding of the

design problem, the ability to reach a consensus solution, and the perceived understanding of the relevant factors.

Comparing between experimental (CCMT) & control test populations:	**Survey number:**	**Sig. (0.05)**	**Statistically significant**
Attitude towards teamwork (*Section 7.3.1*)	1	0.284	No
	2	**0.023**	**Yes**
	3	**< 0.005**	**Yes**
Shared understanding of the design problem (*Section 7.3.2*)	2	0.934	No
	3	**< 0.005**	**Yes**
Degree to which the final solution represents a consensus solution (*Section 7.3.3*)	3	**< 0.005**	**Yes**
Attitude toward design project (*Section 7.3.4*)	1	0.383	No
	2	0.298	No
	3	0.383	No
Understanding of the relevant stakeholders (*Section 7.3.5*)	2	0.663	No
	3	0.869	No
Understanding of the set of factors relevant to the design problem (*Section 7.3.6*)	3	**0.015**	**Yes**

Table 7.23: Summary of statistical results across independent samples.

The next table provides a high level overview of any changes within the experimental population (CCMT) over the course of the project. These questions revolve around the CCMT and its use, and reveal student attitudes towards the CCMT and its impact that improved over the course of the project. The only question for which student opinion of the CCMT did not improve was the impact of the tool on stakeholder understanding. This aligns with one of the two questions that did not achieve a statistically significant difference across populations (*Table 7.21*): understanding of relevant stakeholders. The alignment of these results appears to indicate that the CCMT did not have a considerable impact on students' understanding of stakeholders or their needs. Aside from that, however, the generally positive and improving student attitudes toward the CCMT's impacts appear to support many of the previous findings. These positive attitudes were also supported by student responses and interactions.

Comparing attitudes over time (CCMT only):	Compared surveys:	Sig. (0.05)	Statistically significant
Attitude towards CCMT (*Section 7.3.8*)	1 & 2	0.108	No
	2 & 3	**0.040**	**Yes (increase)**
	1 & 3	**0.007**	**Yes (increase)**
Impact on design problem understanding (*Section 7.3.7*)	2 & 3	**0.015**	**Yes (increase)**
Impact on ideation (*Section 7.3.7*)	2 & 3	**< 0.005**	**Yes (increase)**
Impact on stakeholder understanding (*Section 7.3.7*)	2 & 3	0.065	No

Table 7.24: Summary of statistical results within the experimental population.

The final table summarizes the results of the evaluator survey. In general, these tests show the highest significance values, but still help to support the positive view of the tool that is being generated across the full-range of analysis.

Comparing evaluator results across populations:	Sig. (0.05)	Statistically significant
Overall quality (*Section 7.4.1*)	**0.018**	**Yes**
Understanding of relevant factors (*Section 7.4.2*)	**0.034**	**Yes**
Innovation potential (*Section 7.4.3*)	0.631	No
Creativity (*Section 7.4.4*)	**0.021**	**Yes**
Sum total of other four scores (*Section 7.4.5*)	**0.048**	**Yes**

Table 7.25: Summary of statistical results for expert evaluations of student projects.

When running statistical tests on this number of variables, statistical significance would likely be achieved for at least a few of the tests just based upon random chance. In this study, however, the pattern of statistical significance, and the questions for which significance was, and was not, returned indicates a positive impact on the process of student design teams in this educational setting. In particular, survey responses and informal student feedback indicate a strong impact on the team's ability to work together and develop a shared perspective of both

the design problem and the design solution. This is in part due to the tool's impact on the way in which students understand the relevant factors (constraints) which make up the design problem.

7.6 Second Implementation of the Tool

After the conclusion of the initial research study, the tool was modified and redeployed in an educational design setting during the subsequent semester. This second study occurred in the context of the same course (ME 5682) as the first study, but its goals differed slightly. The first research study provided a large amount of numerical and qualitative data, but lacked depth and detail as a result of the large number of participants. In order to build a better understanding of the tool, its use, and its value, the second study was conducted with a smaller sample of students and was intended to more fully explore the students' perception of the tool.

For this second study the class (and study population) consisted of fifteen graduate students from both engineering and industrial design disciplines. These students were divided into four design teams, all of which used the CCMT (there was no control population for the second study). Given the goal of building a deeper understanding of the tool's use (rather than data collection), this was a necessary concession. While the surveys were once again distributed to the students, limited voluntary participation further reduced the sample size, and limited the value of the numerical data for any statistical analysis. At the same time, the goal of the second study was to focus on qualitative data gathered through focus group exercises conducted after the project's conclusion. This section will briefly discuss the student surveys prior to focusing on the results of the graduate student focus.

7.6.1 Data Analysis: Graduate Research Study

All of the results from the graduate student survey must be viewed with the understanding that this study was conducted with a small sample size and no control population. Additionally, there was no expert evaluation of the design outcomes. Because statistically significant change is difficult to accurately assess with such small sample sizes, data from this second-run study will be summarized and visually compared with results from the first study (experimental population)—rather than covering every question in a manner similar to the first

study. Data will be compared from 'survey 1' which was given at the beginning of the project (*N*=11), and 'survey 3' given at the project's conclusion (*N*=10). The intention of comparing the data in this manner is not to verify results in a statistically significant way, but rather to act as a quick 'sanity check' for the results observed in the first study.

Even visually comparing distributions however, has the potential to be misleading, as small changes to user responses can appear as large fluctuations in the data. For instance, in the first-run study 10% of the total respondents corresponded to approximately 10 students, and 10% of the experimental population corresponded to 6 students. In the second-run graduate study 10% is equivalent to a single student (for survey 3). This means that a single student's negative or positive reaction carries much more weight than it did in the first-run study; even a data entry error can carry a large weight. Still, the distributions between the first-run undergraduate study and the second-run graduate study are remarkably consistent.

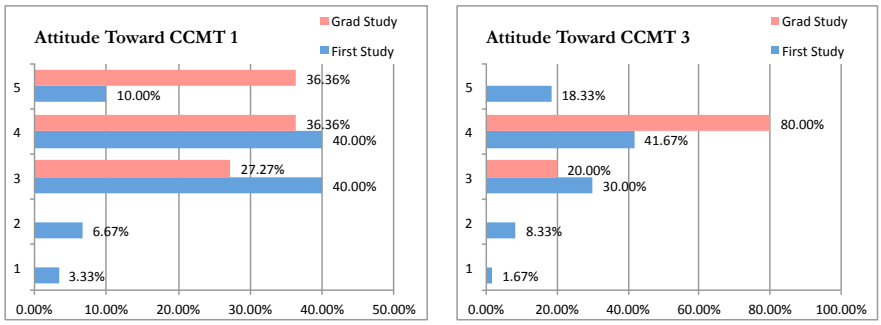


Figure 7.35: Comparing student attitudes toward the CCMT between experimental populations.

Looking at student attitudes toward the CCMT reveals a graduate population that was initially more positive about the tool than their undergraduate counterparts. Every graduate student rated their attitude as a 3 or above, and only 27.3% of the population (three students) provided the neutral response. This positive attitude with regard to a tool which they had not used is likely a combination of many factors, but may be the result of the students' perceived understanding of the tool, optimism about their design project, or trust in the researcher. The undergraduate population saw their attitudes skew more positive over the course of the project. The graduate population's attitude toward the tool converged on the still positive '4' response by the conclusion of the project. Despite changes to the distribution over the duration of the

project, there was not a statistically significant change in the graduate students' attitudes toward the CCMT. At the conclusion of both studies, there was a similarly positive view of the tool from both experimental populations.

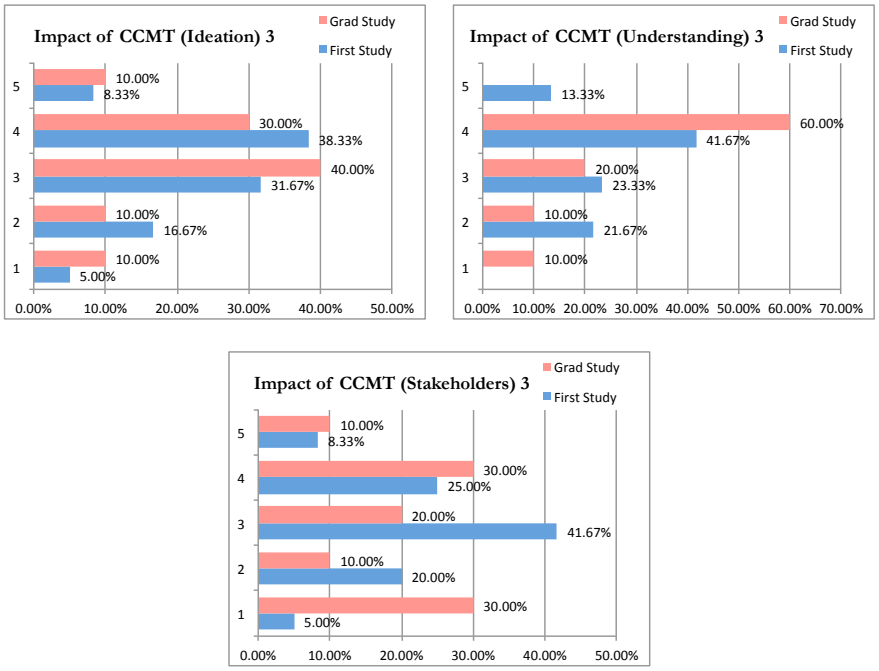


Figure 7.36: Comparing student attitudes about the CCMT's impact on ideation, problem understanding, and stakeholder understanding.

Directing attention to the impact of the CCMT on various aspects of the student design processes, we again see similar results across experimental populations from both studies. At the conclusion of both studies, there was a slightly positive view of the tool's impact on the ideation process. In both instances, there was a more positive view of the tool's impact on the groups' understanding of the factors relevant to their design processes. In fact, the graduate population had a higher percentage of students who viewed the tool as having a positive impact (60.0% responded with 4 or 5, as opposed to 55.0% for undergraduates), despite a smaller number of 5's. Viewing the CCMT's impact on stakeholders, the undergraduates had a largely neutral view of the tool's impact, with the distribution being approximately evenly distributed about the neutral response. The graduate students on the other hand saw a comparative increase in the number of positive responses, but also an increase in the number of strongly negative responses.

This seems to support the findings from the first-run study that there is not a strong correlation between the use of the tool and the students' understanding of their stakeholders (although it *may* still hold value if used properly in the appropriate contexts).

Figure 7.37: Comparing student attitudes about teamwork, shared understanding, and consensus.

Finally, it is possible to compare the impact of the CCMT on aspects of the process related to teamwork, and the ability to develop a shared understanding of the problem and solution. Looking over these survey questions reveals results that are quite similar. In both instances, positive 'attitudes toward teamwork' were maintained throughout the process. There was once again a reduction in the extremely positive responses within the graduate population,

but this was balanced with improved attitudes of those students who initially viewed their groups' teamwork at the level of 2 or 3. For 'shared understanding of the design problem,' responses were once again very similar, and there was positive movement over the duration of the design project. The distributions differed most with respect to the teams' ability to reach a 'consensus design solution,' but the graduate student responses paint a picture that is even more positive.

In conclusion, this data can be interpreted as generally supporting the numerical results achieved in the first-run implementation of the CCMT. This second-run survey data must be viewed in conjunction with the first study, as a result of small sample sizes, limited participation, and the absence of a control population. Still, this data acts as a qualitative confirmation of previous results, and *helps* to support a positive view of the concurrent constraint matrix and its value within the design process.

7.7 Graduate Focus Groups

The small sample size of the second (graduate) study allowed the researchers to learn about the tool in ways not possible given the large population of the first study. The engagement level of the graduate students, in contrast to the undergraduate population, also allowed for more significant discussion of the tool. Further, these students' previous experiences in academia and industry helped to provide a valuable perspective on the value of the tool.

In an attempt to start a dialogue about the value of the tool and its use, thirteen of the fifteen graduate students volunteered to participate in focus group discussions. The focus groups consisted of between three to four individuals and lasted approximately one half of an hour. During the focus groups, students were asked to speak honestly about the values and shortcomings of the tool. The focus groups were conducted as informal conversations in which the students could share and build upon the thoughts and ideas being expressed by the other students. Each conversation played out differently as the topics of discussion shifted based upon the student feedback, but there were five general prompts used to guide the discussions:

1. Students were asked to mark their favorite and least favorite parts of the matrix on provided paper copies of a completed CCMT matrix. They were then asked to explain their choices.

2. How, if at all, was the CCMT valuable within your team's design process?
3. In what ways was the CCMT not valuable? What were drawbacks or deficiencies that you identified in its use?
4. Is the CCMT a tool that you would use again? In what context?
5. Now that you are experienced with the tool, what would you change about its use? How would you redesign it?

After the conclusion of the focus groups, audio recordings were used to analyze the student responses. Responses were clustered by topic, and leveraged in an attempt to identify higher-level patterns and themes within the student responses. The remainder of this section uses the five prompts outlined above to structure the analysis and discussion of the focus group results. While the included responses arose during all phases of the conversation they will be presented using this basic structure in order to logically group similar and connected responses. For instance, students provided insights about the tool's value in response to many of the questions (not just question number two), but these responses will primarily be presented in *Section 7.7.2* which addresses the value of the CCMT. The exercise of marking the least and most favorite parts of the matrix will be presented first, as it serves as a quick refresher for the basic components of the CCMT matrix (discussed more thoroughly in *Chapter 6*).

7.7.1 Marking Favorite and Least Favorite Parts of the CCMT

In an effort to help students articulate the positive and negative aspects of the tool, each student was provided with a paper copy of a completed matrix and asked to mark their favorite and least favorite portions of the matrix. As these focus groups were not conducted in front of computers running the CCMT software, providing the paper matrix ensured that the students had as accurate a sense of the tool as possible. They were asked to mark their favorite portions using green stickers, and their least favorite portions using pink/red stickers. They were told that they were not required to place any green stickers if they did not have portions of the matrix they liked, just as they were not required to place stickers corresponding to their least favorite components if there was nothing they disliked. Students varied in how many stickers they placed,

with some students placing only one favorite and one least favorite, some placing multiple stickers in both categories, and others not placing any for a particular category. After placing the stickers, students were also asked to annotate and discuss their marks in an effort to better identify their actual intent. Copies of the marked sheets can be seen in *Appendix L*.

After the conclusion of the focus groups, the student marks and annotations were aggregated in order to better track the students' collective assessment of the CCMT components. Looking broadly at the placement of likes and dislikes quickly reveals the aspects of the tool that students found most valuable. Doing so also depicts a generally positive attitude toward the tool. As a group, students placed a total of 29 green "like" stickers, and only 15 pink "dislike" stickers. To best present the aggregated data, likes and dislikes have been divided and one table and figure are provided to summarize each. The figure acts as a visual clustering of the students' marks, and has been condensed to allow for a more easily interpreted representation. Each stack of marks is labeled with a number that corresponds to that item in the associated table. The tables enumerate the student responses and provide a bit more detail through the inclusion of a few relevant annotations. Greater detail and explanation for many of the verbal descriptions of the students' placements of both likes and dislikes will be provided in the subsequent sections.

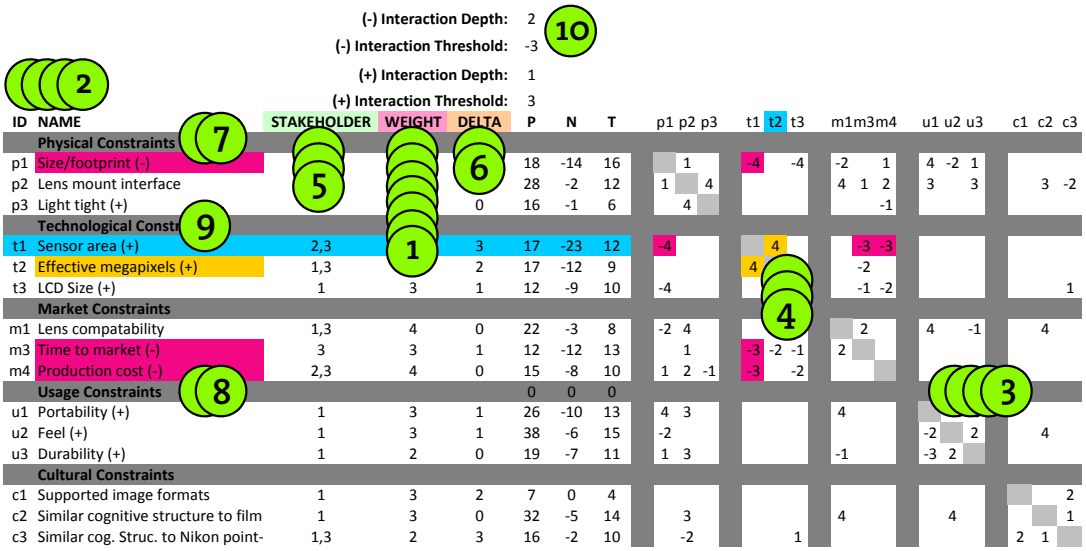


Figure 7.38: Aggregated representation of the placement of "likes".

ID	Description	# of marks	Relevant annotations
1	Weight	7	Which constraints were most important; important part of the matrix
2	Constraint column	4	Helped focus decisions; forces you to think about constraints
3	Constraint interactions	4	Helped in understanding the connectivity of onstraints; forced to think about all the interactions so I could figure out which were essential; + and - #s
4	Dynamic highlighting	3	Very visual; great color coding
5	Stakeholders	3	A pretty good innovation; consider everyone involved
6	Expected rate of change	2	
7	Physical constraints	2	
8	Usage constraints	2	
9	Technological constraints	1	
10	Interaction depth	1	Automatically shows second order interactions after we filling out simple constraint interactions we know
	Total:	29	

Table 7.26: Tabulating the placement of student "likes".

The importance of the 'weight' column clearly shows through, as it was marked on half of the students' sheets. This is likely due to its role in creating dialogue and forcing students within the group to reach a consensus (discussed in more detail in the next section). The 'constraint column' received four marks, but it is worth noting that it would have been possible to include marks for items 7, 8, 9 (physical, usage, and technological constraints) within this count as well. This would have brought the tally for the constraint column up to nine, but these are left separate as they were referenced individually by the students. In total the thirteen students positively marked a total of 29 items within the CCMT.

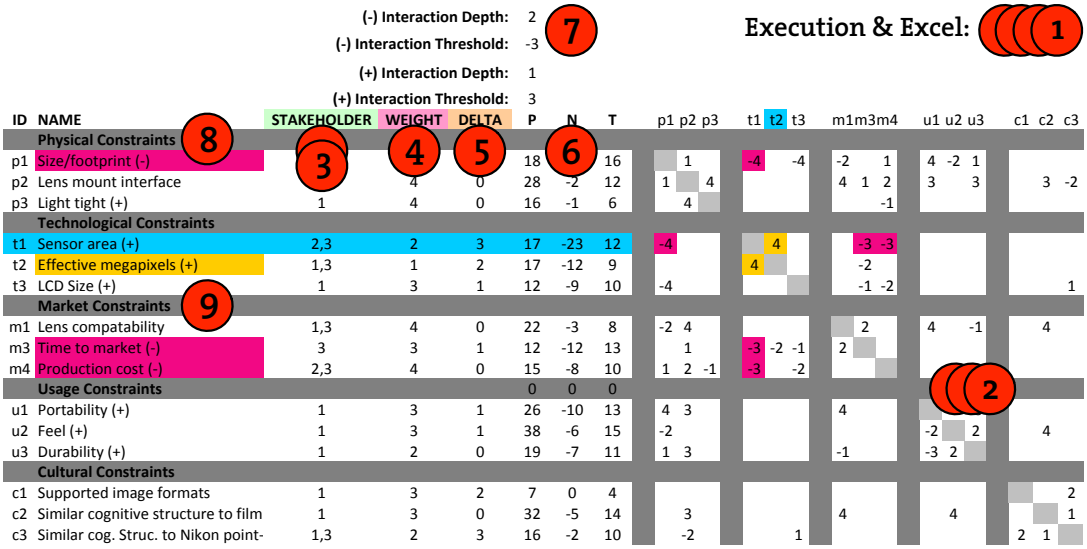


Figure 7.39: Aggregated representation of the placement of "dislikes".

ID	Description	# of marks	Relevant annotations
1	Execution and Excel	4	Better instructions; creating new rows (x2); want comments and definitions when mousing over constraints
2	Constraint interactions	3	Lots of arbitrary entries; not sure how to weight
3	Stakeholders	2	Incorporate with weight column
4	Weight	1	Incorporate weight and delta better
5	Expected rate of change	1	Incorporate weight and delta better
6	Connectivity columns	1	Was confused on meaning of P, N, T
7	Interaction depth	1	Concept of multiple interactions without a visualization
8	Physical constraints	1	Harder to define than the others
9	Market constraints	1	Doesn't seem applicable to our project...further down process
	Total:	15	

Table 7.27: Detailing the placement of "dislikes".

The first thing to notice is that students only placed 15 "dislike" stickers—roughly half as many as "likes." Of these dislikes, the most frequently marked item did not concern the conceptual structure of the tool itself, but instead referenced aspects of the tool related to its use, execution, or less than ideal fit with Microsoft Excel (e.g. better instructions, difficult to add a row in Excel, etc.). Removing these stickers further reduces the number of dislikes to 11. The next most frequently marked aspect of the tool was the 'constraint interaction matrix.' Students

referenced the time it takes to populate and the somewhat arbitrary nature of quantifying these relationships, as reasons for disliking the interaction matrix. The only other item that received more than one mark was the 'stakeholder column' (two).

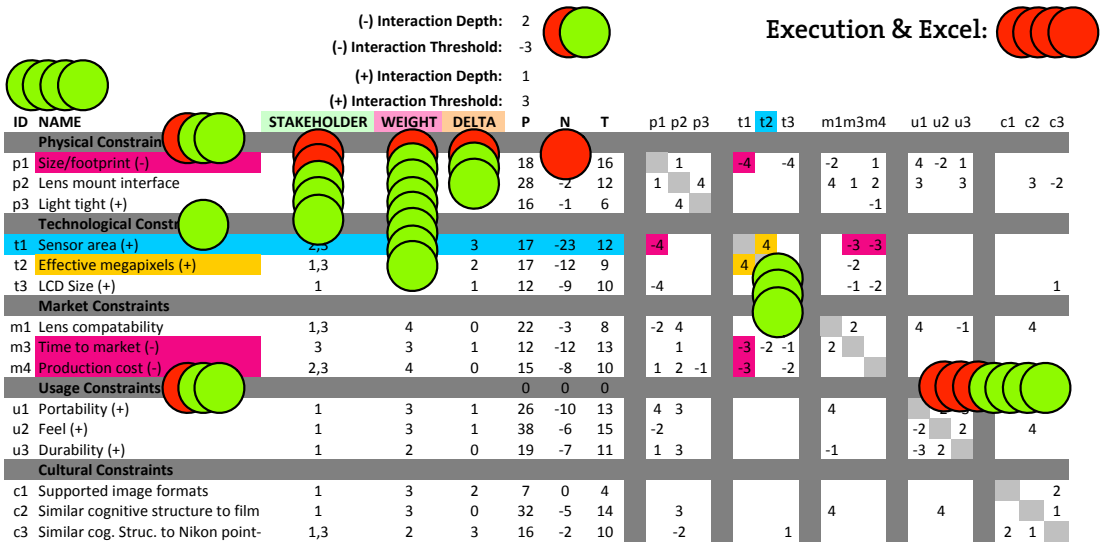


Figure 7.40: Aggregated representation of the placement of "likes" and "dislikes".

Beyond the total number of likes and dislikes, comparing the placement of the marks reveals that both were distributed over the entire matrix. Within these responses, however, there were clearly parts of the CCMT for which the likes drastically outweighed the dislikes—most notably the constraints, constraint column, constraint weight, and the dynamic highlighting. Students were more split on the value of the constraint interactions, stakeholders, and expected rate of constraint change. The disagreements for stakeholders, weight, and delta can be mitigated somewhat as three of the four responses were suggestions to combine these columns, in some form or fashion. The P, N, and T connectivity columns were the only aspect of the CCMT matrix itself that received more negative than positive votes (one), but the student cited a lack of understanding of the "…meaning [of] PNT." While these results seem positive, a deeper exploration of the qualitative feedback that arose during the focus group exercises is still necessary.

7.7.2 Value of the CCMT

Throughout the course of the focus group exercise students recognized a number of ways in which the tool benefitted their design processes, as well as potential value in future contexts. This section covers the positive impacts of the CCMT, and supports those assertions with a number of quotes drawn from the student focus groups. As a result of the informal nature of these conversations, some of these quotations are a bit difficult to digest. The students' words are reproduced as accurately as possible, but some of the quotations have been altered (through the use of bracketed words) in order to maintain their readability, and convey their original intent.

One of the most recognized benefits of the CCMT was the role it played in the *exploration of constraints*. The students consistently mentioned the value of the tool in helping the design teams to explicitly identify and acknowledge the constraints at play within their design process. This particular benefit was brought up in each of the five focus groups, and in most cases it was addressed on multiple occasions throughout the discussion. One student noted that the CCMT, "…at the very least, is good for making us think very explicitly about *what* we are trying to design, and why we are trying to design it." Many students referenced that populating the constraint column encouraged them to look at the constraints that arose from each of the five categories. In doing so, the CCMT helped the teams to provide structure to their chosen design problems, and one student noted that in, "…filling out the CCMT, we had to bound the problem. We had to say, 'what really is our goal here guys?' because at that point we had a pretty broad definition [of the design problem]."

One student noted that the structure of the matrix itself forced the team to consider a broader set of constraints than they might have otherwise, stating: "Having these separate fields [for each constraint category], and forcing you to take each one [individually]—not just constraints in general. I thought that was really good." That is, having the matrix divided into five specific constraint categories forced the team to think about constraints they might not have otherwise attempted to explore. Another student in the same focus group built on this line of discussion, by pointing out the value of the matrix as a tool for visual representation: "We weren't thinking about cultural or market [constraints] at the time, but we have the blank spaces and we got to think about it. So, it kind of forces us to think about those *other* constraints."

Many of the students also referenced the value of the CCMT not only in recognizing the constraints, but also in recognizing their relative importance. One said that for his group, "…this is when we actually sat down and thought of our design properly. When we were going through this [CCMT], was actually the time when we had to stop and put everything on the board and figure out what was the most important in each category…. It helped us to organize our thoughts about what was actually important." This leads to another role of the CCMT, as an important collaborative tool. Because the matrix was populated in a collaborative way, it forced the students to articulate to the entire group the constraints most relevant from their individual perspectives. Doing so helped many of the design teams to *build a shared understanding of the design problem* or, as one student put it, "negotiate common ground."

One student stated that, "…[the CCMT] allows for common ground to happen, and for the negotiation of what we think is important? And what we think is not important?" He explained that rather than having everyone work independently and then return to a group setting with different notions of importance, "having something like this… [as] a template of common ground, definitely holds value." Aside from merely recognizing the constraints, this was the second most often cited benefit of the tool. Another individual said of the CCMT: "I think it is a good tool to help everyone get on the same page because it puts everything right there in front of you. You can see it all at once." In a group comprised of diverse perspectives and potentially diverse areas of expertise, "the [CCMT] definitely helped starting the dialogue about what we all agree is important… especially if you are on a multi-discipline team. Because I definitely noticed that [two of my team members] didn't necessarily look at the problem the same way I was looking at the problem." Another student expressed: "We each have different thoughts about what is important for the design, but [the CCMT] kind of unified each and every one of us. It brought us together into one focus where everybody was on the same page." This student also noted that they were able to "…come to an understanding of the overall objective [of the design process]."

Some of the students not only referenced the constraints as a way to build this shared view of the design problem, but also drew specific attention to the matrix's 'weight' column. Saying that, "…it helped unify us. Making constraint[s] is one thing, but figuring out what is important is another; which the weights helped us [to do]." Reinforcing the importance of the weight column, another said: "I liked the weight because it forced to us sit down and agree how

important all of our different constraints were, what we needed to address, and what could kind of be pushed aside." All of these comments about populating both the weight and constraint columns echo the findings from the marking exercise, in which those were the two most frequently "liked" components of the matrix.

The CCMT helped the design teams to develop a shared view of the design problem, and forced them to collaborate towards a jointly held sense of importance. It also helped the students to find common ground about how those constraints might be best addressed. This negotiation, however, was not limited to just the constraints themselves, and many students referenced the role of the CCMT in helping them to *recognize and reach a consensus on the important constraint interactions*. One student stated: "I think [the CCMT] helped in finding the relationships between constraints which were invisible [just] by looking at them. Once we had the second part of the matrix [interaction matrix] we were able to compare how one constraint would affect the others…. I think it was helpful in getting to know the interconnections between the constraints." Another student in the same focus group referenced his team's similar experience by saying, "…filling out the table forced us to go through and really look at all the possible interactions between all of the components, and then pick out the ones we thought might actually be important. So it forced us to really go through and explicitly look at all of them together." Another individual called attention to the CCMT's role in helping to identify important interactions, and helping the team to reach consensus: "It really helped to show the constraints that were connected—that we had thought about in a way—but hadn't really tied together as much as we should have." He went on to discuss a shared understanding of these relationships that emerged, saying, "it put us all on the same page [by] showing us how certain constraints tied together. [What it] really, really helped with, was getting us all on the same level…."

Certain students also expressed the value of the tool in providing recognition to *second order constraint interactions*. Multiple students communicated that this was probably the single most unique attribute of the tool. Others noted that this aspect of the CCMT has the potential to provide greater foresight, and will help to anticipate unforeseen complications that may arise within the design process. When asked about the general value of the tool, one student with professional experience within a large engineering organization called out these second order interactions: "One thing that I still think is pretty big is the fact that it highlights the second order interactions. The first order interactions—one thing directly affects another—anyone can

figure that out. *This* directly affects *that*. That's kind of how we are trained to think. But that second level, that's the one that most people won't follow directly…. It was kind of entertaining to go through it, and see the really big second level factors because a lot of times you are like, 'how is weight affected by that? And then you are like ohhhhh, OK!" He went on to state that he thought this was one of the aspects of the tool that has the most potential within an industry setting.

Another student said, "I think the second degree interactions are pretty useful too because you don't find yourself changing something, releasing the product, and going 'Oh, we didn't realize that was gonna [sic] happen.'" Another student, who echoed these sentiments, also identified why recognizing these interactions actually matters: "Showing how one constraint affects the other, I think that was really important. That helped out quite a bit because it's things that you don't really think about. That's something you might not think about or find until later on in the prototype process [or] when other people are using it…" but when you do, "…you realize it could have saved you time, it could have saved you money, it could have saved you a lot of headache. I think that was really important."

Moving beyond the constraints themselves, students also noticed the tool's role in helping them to recognize the varied sources of the constraints. A number of students spoke about how the CCMT helped their teams to view the design problem from the *perspectives of multiple stakeholders*, and that, in doing so, the CCMT helped them to identify new and important constraints. One individual recounted that in their team's design process all of their initial thinking and constraints centered on a single stakeholder (a hospital patient), but "…at some point we realized that we were designing for the nurse also [as a result of filling out the CCMT]." In a subsequent focus group another member of this same team stated: "I liked the stakeholders [column]… because this is something you have to consider, and it really forces you to [question] 'who do I have to think about in this situation?' It's not just the nurses and the patients. It's also the hospital administrators, the people that have to train the nurses to use the tool, [the] patients' families because they might have to take care of them at home, [the] manufacturers, etc." Referencing his own experiences, another student brought up the importance of exploring solutions from the perspective of various stakeholders prior to solidifying the design. He stated that in engineering capstone projects it is tempting to jump straight into building or constructing a solution, but that "if you just go straight to building… you can get really off track." He noted

that in this context, the CCMT acts as a "…sanity check that says, 'what does this do? Why are we doing this feature? What is the value for each of these things for each user?'"

Students from one particular design group also discovered another unforeseen benefit of the tool. In using the CCMT throughout their design process, they found that the tool helped them to not only execute the design process, but to *plan the design process* as well. They found that the CCMT acted as a sort of informal project management tool that helped them to "…construct a timeline" and pace their design activities over the course of the project. Speaking about the tool's potential value in this role, one of the group members stated: "This will help you outline the parts where you are going to run into real difficulties. The parts of the process where you are going to face the most struggles, because it tells you what constraints are going to be affected by what other constraints. Where you have the most interactions is where you are going to have to spend the most time. I think, from that aspect, it seemed to help us lay out a good time frame for getting things done, because we knew where we were going to spend the most time thinking about things, talking things out, scheduling meetings, etc. There were parts of the project where you could just say, 'everyone go, come back on Monday, and we'll have this done.' There were other parts where we knew, 'we need to meet for three hours and talk about this,' [in order to deal with those more tightly constrained and interconnected aspects of the project]."

7.7.3 Drawbacks and Deficiencies of the CCMT

In an attempt to present an honest picture of both the values and deficiencies of the CCMT, students were also asked to candidly discuss the limitations and drawbacks of the tool. In doing so, they recognized a number of the known limitations of the tool, but also identified a few previously unrecognized problems and complications. This section presents the negative aspects the CCMT, as identified by the students. It supports these observations with quotes drawn from the student focus groups.

One of the very first students to respond about the tool's deficiencies noted that he "…wasn't entirely sure what it was supposed to tell [him]." This was a fairly common sentiment early in the tool's use, as many students across both studies were initially under the impression that the tool was supposed to provide a solution or a specific output. However, according to many of the students after they had some practice with its use, they realized that the tool was not

intended to provide a specific output. One student offered a fairly representative response: "Starting with it, it was a little difficult figure out exactly how to use it, and how everything tied in together; but once we actually started using it and putting everything in, it got easier and really made a lot more sense."

While the CCMT's role in helping to define the constraints on a design problem was seen as valuable by the majority of students, the constraint relationships (as mapped in the $N \times N$ interaction matrix) received more of a mixed response. The majority of students saw the value in tracking these relationships, but many had issues with how the interaction matrix was actually populated. Primarily, they referenced the somewhat *arbitrary nature* of scoring the constraint relationships. One student noted that it "…felt a little bit arbitrary how we were assigning the numeric values because, at this stage, it is to some extent kind of arbitrary." Another individual mentioned that evaluating "…the relationships between each factor [requires] making assumptions, and [leads to] thinking like, 'I *think* that's a four, I *think* that's a three.'" In response to this particular comment, another student immediately built upon this sentiment, but also recognized value even within these arbitrary evaluations. Saying, "while I didn't like having to put a number to things, it *was* useful to force us to explicitly think about all the interactions; and forced us into a discussion of which ones really mattered."

Although these are certainly issues, some of these drawbacks are potentially the result of the design project in which the CCMT was tested. Students noted that *the structure of the design project* may not have been ideal for the application of the tool. Notably, students pointed out that the truncated nature of the project (the project's final deliverable was a design concept rather than a completed design solution) kept some of the tool's features from being relevant. It also made the use of certain parts of the tool seem forced. One student stated that the tool "…brush[ed] up against the limitations of what we were doing in lab," because of the length of the project and the absence of the need to actually design solutions that address all of the constraints. For instance, he referenced a constraint on their design related to the creation of a leak-proof seal, but noted that they never actually had to confront this constraint because they were not responsible for the creation of a *fully functional* prototype. Their team could simply state that the design would "…magically not leak."

Another student noted that the CCMT might actually have increasing value a bit further into the design process: "I think it would be nice to redo [the CCMT] after having already made

one semi-functional prototype." After building a semi-functional prototype this group identified constraint interactions that were "…not really foreseen at the beginning, and only became apparent after we started fabricating something." He felt that the CCMT's usefulness would "absolutely" increase as they pushed forward to a solution. He continued: "I feel a lot of the things I would put into the matrix are things that would come in farther down the line like strength of materials, and things like that." Another student referenced that the interaction matrix in particular would be increasingly useful in the "…modification stage. Where we have a design, have tested it, and now have more of an idea that *this* is really affecting [*that*]." He felt that this information could then be input into the matrix, and "…going forward, when we say we are changing *this*, we will more clearly understand how [it] is going to affect other aspects of the project."

With regard to the timing of the CCMT's application, it was also brought up that many of the constraints within the matrix could only be populated once some decisions about the design had already been made. "[The CCMT] only becomes useful after you start to make those decisions about what it is *actually* going to be." In designing a solution to help nurses assist bedridden patients to use the restroom, one individual noted that many of the constraints would be vastly different depending on if the group decided to design a new bed pan, or a new device intended to help lift the patient—each would represent a considerably different set of constraints. Another student stated that, "you really have to get to a certain point in the project where something like this [CCMT] comes in. You have to do a certain amount before this is worthwhile, and I'm sure with a capstone, or something like that, they'll get there." However, this student was not entirely certain that his team had reached the point that the effort to populate the tool was entirely worthwhile. He said that, "I think we were pushing it, and it was almost when we were done that [we were] ready [to populate the matrix], because we *knew* the interactions at that point."

A few students also brought up that because the CCMT's was applied in such a limited design process, and because it was to be completed as a part of a class assignment, there was a sense that the entire matrix *had* to be populated, and every feature *had* to be used. These students noted that this led to specifying constraints and interactions, before it was appropriate to do so. "It sort of screams fill me out all at once," one student said. Once recognized, this led to a discussion of how to help students "…pump their brakes" when filling out the CCMT. Rather

than filling it out all at once, or specifying too many constraints too soon, it became a matter of trying to encourage design teams to populate the matrix at a pace appropriate to their specific process. One student noted that "…the market and cultural constraints really dictate your goals; and physical, technological, and usage constraints determine how you go about accomplishing them."

He felt that they should have started with the market and socio-cultural constraints because those constraints would apply almost no matter what they decided to design. From there, starting to branch into use and the other constraint categories as their knowledge was solidified. Another student built on this, saying that filling out the constraints too early can create a sort of "…self-fulfilling prophecy where you end up designing things to the constraints you wrote down that were nothing more than guesses in the first place." Essentially, it may be possible to establish constraints with a solution already in mind, and in turn be guided towards that solution. This is an extremely relevant insight, and something that must be addressed in any future implementation of the tool.

One student also noted that the arbitrary interaction scores, combined with the feeling that the entire matrix needed to be populated at once, led to the reduced visibility of key interactions that were actually driven by observation. He proceeded to communicate that his team had populated the entire interaction matrix in one sitting, going row by row through every possible interaction. The group's first rough prototype, however, led to the identification of a few constraints that interacted much more strongly than they had anticipated. These constraints interacted in a strongly negative way and represented a substantial trade-off that would have to be addressed within the design. The interaction matrix was updated accordingly, with high values being entered in the appropriate cell, but the student felt that this important trade-off was actually "lost" within all of the other highly speculative interaction values. This led the focus group to discuss that the tool would likely be more useful if it was populated more slowly, as new interactions and data actually emerged from the process.

A number of other drawbacks related to the form of the matrix itself were also identified. These were typically not related to the conceptual structure of the CCMT, but rather its execution and construction. While there was not a universally desired form, many of the students made reference to wanting a more simple, or more visual, version of the matrix. One student expressed that he "…would like to use this in a simpler form," stating the desire to

populate the interaction matrix with only binary measures of +, -, and 0. Although this is actually supported by the matrix, he did not recognize it as such.

Other students referenced the slow process of actually filling out all of the matrix's fields, saying that it can be "…tedious to do, and took a long time to populate." When asked about the drawbacks of the tool, one student said: "The data entry, that's honestly the only big downside for me is having to go through and put everything in." Many other students also referenced the fact that the Excel format made the data feel a bit inaccessible. One individual said that "looking at an Excel spreadsheet…" led him to say, "what in the world does this mean?" And that it "…is a little difficult to… quickly and easily draw conclusions from [the matrix]—we are humans, we aren't spreadsheet readers." Another student, from an Industrial Design background, also noted the way in which the data was visually presented, saying "I find it a little hard to use this, probably because I am a very visual person—I prefer connecting constraints using lines."

7.7.4 Reuse of the CCMT

Upon being asked if they would reuse the CCMT, student responses were generally positive. All thirteen of the student participants said that they would reuse the tool. At the same time, a number of the students put forth qualifications for its reuse: some said that they would use it in a different context, for a different type of design project, in a modified form, or only a portion of the tool. Still, the fact that the students saw enough value in the tool to want to reuse it—even in a different context or form—can be seen as affirmation of its value to a group of individuals experienced with its use. A number of students also mentioned their intentions to apply the CCMT in their own graduate work, or any manner of personal projects. Again, affirmation that the students perceived actual benefits of using the CCMT.

The students referenced a wide range of contexts in which they thought the CCMT would provide enough value in order to justify its reuse. Speaking from his experience in a professional setting, one student said that he would use the CCMT "…more on the software development side." Stating, "the people I'm working with are trying to solve a very, very complex problem with a piece of software, and I would like to see them [use this] because they have very little direction right now. They are just kind of testing usability things as they go along

without answering any deeper questions. I think this might be extremely useful to force them to sit down—just like it did for us—and initiate a discussion to get them to explicitly state their goals and what they think their constraints are because, right now, they have no clue."

A graduate student studying manufacturing systems stated: "I will be using this for my Master's thesis, where I will be working on optimizing cooling channels for hot stamping dies. There, a lot of factors need to be considered like coefficients of friction, surface hardness, etc." He noted, however, that he would obviously have to modify the matrix, likely removing the categories of constraints (socio-cultural and usage were specifically mentioned) that do not apply directly to his particular interests. When speaking about his own experiences in industry, another student expressed trust in the tool by saying that the decision to reuse the CCMT "…depends on the scale of what you are doing, and the value of what you are doing. Small project—I probably might not do it. But if it's an important, big project, where my ass is on the line, then I would *have* to do it."

Speaking about his own entrepreneurial venture that he plans on undertaking upon the completion of his degree, one student commented: "Definitely want to use it again in more of a business context. Having seen this before I definitely would have used it for capstone or senior design project, because we just used a regular QFD [House of Quality] for that, and didn't get too much out of it." Asked to provide a bit more detail on the comparison to the House of Quality he said, "…seeing how things more positively and negatively affect other constraints, I think this does a lot better job at that than the QFD does. This just seems a lot more user friendly after getting into it. It makes a lot more sense, and is more thorough than the QFD as well."

One student who is particularly experienced with the engineering design process saw the CCMT as a potentially valuable tool to teach others how to approach the design process. "I'd use it to teach people the design process…," he said. Referencing his future in industry, he continued, "we're probably all going to end up in management positions, so if I had someone who just wasn't thinking of the big picture when they were working on product design I would sit them down and say, 'Hey, here's [the CCMT].'" Speaking from another experienced design perspective, an industrial design student stated, "I would use this concept in my other design projects, but I wouldn't use the tool exactly by itself. I would use the concept behind it of having all these things, and forcing myself to actually create relationships between each one of them.

But, I would do it in a much more visual way. I definitely think the concept is very helpful." While placing caveats on its use, this feedback from an industrial design perspective is particularly encouraging. It shows that the core concepts of the CCMT may hold value beyond engineering design, and engineering design education, even if its current form is less than ideal for other user groups.

Another student also recognized the potential value of the tool in contexts apart from design, saying, "I feel there is a lot of value here even beyond a product design structure." He went on to discuss the CCMT's value with respect to a previous work experience generating measures for human performance. He mentioned that the tool would have been really useful in helping to establish a shared sense of direction within a team struggling to overcome disagreements about what was important to measure and how to allocate resources. The applicability of the tool in contexts beyond product design was stressed a number of other times as well: "I really like this tool. I think it would be a much useful tool that I could use in a lot of other areas too." And another noted, "I really liked the interaction matrix. I think it's a very good tool if you are going to apply this for any kind of decision making process, since it helps us to think in a multi-dimensional way."

7.7.5 Redesigning the CCMT

The final point of discussion within each focus group centered on envisioning future possibilities for the CCMT's design and implementation. Students were encouraged to suggest changes and additional features based upon their use of the tool, and their own perceptions of what *might* be valuable. Students were instructed to suggest these ideas based upon value and desired functionality, rather than based upon any sort of technical limitations (changes only implementable outside of Excel, for instance). They were also specifically told that they did not need to be limited by the CCMT's current structure, and that "anything is possible."

Referencing his current job, one student described the nature of engineering work at a major engineering corporation: "We are very data driven. Design doesn't really factor into it, and it is very much about requirements and the tech specs." He went on to discuss that the CCMT's value is in its ability to track and balance more qualitative (non-quantifiable) constraints at a system level. Speaking of the CCMT's design, he said, "…you need it to be like this," because

"…a lot of this you couldn't put [rigorous] numbers behind ever." At the same time, he highlighted the importance of data-driven quantitative metrics, and questioned if it would be possible to include both qualitative and quantitative data in the same table as it becomes available. "[The CCMT] very much operates on good/bad. At some point though, it's not a matter of good and bad, but how bad? We know this is going to add cost, or make it less portable, but at some point we have to ask *how much* less portable." Doing so would potentially allow the tool to transition more smoothly throughout the entire engineering design process; moving from the more conceptual design phase into the detailed execution of a highly engineered object.

When asked to redesign the tool, many of the students brought up changes intended to eliminate challenges associated with the CCMT's current implementation within Microsoft Excel. One student lamented the usability of the tool, saying that adding rows was overly difficult (a point that was brought up numerous times); and that because the program had no ability to 'undo' the last action (a result of how Excel VBA programs are implemented), their team was forced to recreate the constraint matrix in another Excel workbook before copying it into the CCMT. Many other Excel–related issues were breached in these discussions as well: the inability to sort the matrix based upon certain factors (weight, rate of change, connectivity, etc.) without "breaking" the interaction matrix, poor program performance, and the visually inaccessible nature of the spreadsheet were all referenced as things which could be improved.

Also with regard to the implementation in Excel, a number of students referenced how much they liked the tool's ability to dynamically highlight the active constraint and its interactions. Multiple students, however, pointed out that they wanted some sort of secondary highlight, as to better call attention to *both* of the constraints involved in the currently selected pairing. Saying that while the current highlight system makes it obvious one of the two active constraints, the other still must be matched using the unique constraint ID (moving the cursor down the constraint column, rather than across the constraint row, was identified as a workaround for this problem by some, but not all of the students). In order to make both of the active constraints more evident, text boxes at the top of the spreadsheet that list the two constraints, as well as a lighter blue highlight in the constraint column were both suggested as possible design changes.

Based upon student responses, it appears that many of their issues with the CCMT revolved around these shortcomings of the tool's implementation within Excel. One student noted, "with the Excel challenges aside, I think it's [CCMT] great." But there were still other suggestions which surfaced. One student wanted the ability to associate comments and descriptions with each of the constraints in order to provide a bit of extra detail: "Say you have a [constraint] like 'durability,' that can mean a bunch of different things. Having the ability to hover over that, and have a pop-up where the person who put it in there can explain what they mean [would be very helpful]." He wanted to know what 'durability' meant to the person who originally put the constraint into the matrix: does it mean "…it needs to last a long time, not break, or… the strength of material?"

Another student felt that some of the columns to the left of the interaction matrix could be implemented in order to provide more usefulness to the design teams. Speaking about the connectivity columns (*P, N, T*) and the 'weight' column, one student said, "…I think those are useful things to be quantified, but I think they can be implemented better. You can have something interact with twenty other things, but if only one of them weighs heavily on the product I think that needs to be taken into consideration." He suggested that the summed positive and negative interactions in the 'P' and 'N' columns "…should be adjusted for weight…," in an effort to indicate a more authentic sense of the constraint's importance.

A number of students also referenced difficulties associated with initially understanding how to use the tool, or the instructions included within the Excel file. A few students noted that because of the provided documentation they did not even realize that it was possible to include negative interaction values within the table. A few more pointed out that watching an Excel demonstration is no substitute for using it yourself, or receiving instruction whilst using it. In order to potentially remedy this, one student suggested video walkthroughs explaining how to use the CCMT, and describing each component's role within the design process: "For the most part, I thought that [the CCMT] was really well done…," but that he would think about adding "…more of a tutorial that you can go through with it as a first step for people using it." He continued, "the instructions were good, but it is still a lot to think about before you get into it. Once you get into it's a lot easier, so maybe a YouTube video that you could do to have people see it." Within any academic setting it is not likely that all of the design teams will be ready to begin using the CCMT at the same time. As a result a web–based introduction, that can be

watched, or re-watched, whenever it is needed may be able to provide a more timely and understandable introduction to the tool, its use, and its value.

7.8 Next Steps: Future Research Contexts

7.8.1 Academic Contexts

In order to better assess the CCMT's value, continued deployment and testing will be critical. As the CCMT is geared toward understanding and exploration within real-world design activity, actually applying the tool is the only way to judge its fitness with respect to its intended purposes. Academic contexts represent one avenue along which this continued application and research can occur, but there are possibilities for implementing the tool within actual design practice as well.

The initial CCMT study was conducted in a mixed classroom setting during autumn semester 2012 and spring semester 2013 at the Ohio State University. Beyond the 2013 semester, there are plans to integrate the CCMT more thoroughly into the instruction of ME5682/ISE5560. This will primarily consist of the tool's application in each of two consecutive lab projects, with the first serving as a 'dry-run' with the tool, allowing the students to become more comfortable with its use and operation in a more highly constrained design context. The second will be a more complete implementation within a real-world design context.

While ME5682/ISE5560 has proved an appropriate test bed for the CCMT, the student design projects in this course are inherently limited in scope by the university's semester structure—as projects must be completed by the end of the term. As a result, these design processes are artificially truncated. Every project only touches a small portion of what would be considered a complete real-world design process, and few are ever forced to confront the realities of actual design application; product architecture, fabrication, design for assembly, etc. are rarely discussed. While this is a reality of the university structure, extending the use of the CCMT to more 'complete' design processes is likely to extend its benefits as well, most likely as a result of many features specifically structured to help designers anticipate the effects of change across the full set of constraints. With that in mind, finding avenues for application alongside undergraduate capstone projects, undergraduate honors thesis projects, and graduate work

within the department and the college may prove a vital next step in the continued application and evaluation of the CCMT.

7.8.2 Practical Contexts

If promising results and significant benefits can be shown across a wider variety of academic settings and design projects of increasing scope, it may be possible to find partners within practical settings who are willing to deploy the tool. To be more widely used, the tool would have to demonstrate an ability to successfully confront the realities of practice—offering value in the face of significant time and cost pressures. Doing so would be another step in gauging the CCMT's usefulness within real-world design processes.

In order to accurately gauge the CCMTs effectiveness, it would have to be employed across multiple project scales. Implementation within smaller design projects (with fewer components and smaller teams), and for larger more complex design projects (which comprise many components and multiple disciplines) is equally important. Ideally, the CCMT would function well across a range of scales, but it is entirely possible that it is better suited to one or another. Additionally, to test the CCMT's full value it would have to be deployed from start to finish within these real-world processes—stretching from exploration and concept generation all the way through to the final production and release of the artifact. Preferably, it could be deployed in projects that stretch over multiple design cycles, as in the case of a product with multiple generational variants, thus allowing for the tool to be tested as an avenue for knowledge management as well.

Regardless of the exact setting, however, the CCMT needs to be deployed further in order to assess its true potential. This educational design study has illuminated the CCMT's promise, showing that it can offer benefits to team work and exploration in addition to improved solution generation. Without further testing and implementation, however, the ability to speak generally about the worth of the tool is speculative. At the same time, the CCMT is firmly grounded in complexity management principles and was designed as a framework to assist designers, rather than as any sort of panacea. The CCMT will hopefully provide a shared language and framework that will aid design teams in attempting to understand and manage the constraints that make up many complex design processes.

7.9 Conclusion

The evaluation of any design tool is not an easy task. The difficulty of evaluating the CCMT as a design itself is compounded by attempts to measure the impact of the tool on an inherently imprecise cognitive activity—the act of designing. Accordingly, every aspect of this study was designed to assess the impact of the CCMT on the factors which contribute to the act of design in an academic and team-based context as accurately as possible. These factors included factors such as teamwork, the team's ability to develop a shared view of the problem or reach a consensus solution, the students' understanding of stakeholders and other relevant factors, the impacts of the tool on the final design solution, and the students' attitudes toward various aspects of the tool.

In order to construct a more accurate picture of the CCMT's value two-studies were conducted. The first was a data-driven implementation in which approximately one-hundred students, divided into control and experimental groups, used the tool and provided feedback. This study was intended to test for statistically significant benefits of using the tool in an academic engineering design context. The second study was conducted with a much smaller group of graduate students, but was intended to explore student opinions, aspects of the CCMT, and elements of use that were concealed in the data of the first implementation. This second implementation was much more qualitative in nature, and relied heavily on informal interactions, evaluations, and a focus group study.

The first study returned generally positive results, particularly with respect to the value of the CCMT's role in a collaborative design setting. Each of these results was supported by positive student attitudes toward the tool itself, and toward the role it played within their design process. Additionally, many students expressed interest in using the CCMT again for some future application. In the second study, the CCMT's value in a team design setting was once again recognized as a large benefit of its use. Students consistently recognized its role in helping their teams to explore the design problem, and explicitly acknowledge the constraints within the design space. Beyond that, students identified the tool's value in helping to identify and understand constraint interactions, recognizing constraints that arise from different perspectives within the system, and aiding their teams to better anticipate potential complications. At the

same time, student feedback (from both studies) was not universally positive, and students identified a number of aspects of the tool that need to be considered and revised moving forward.

Despite the inherent difficulty of evaluating the Concurrent Constraint Management Tool, these studies, when viewed in conjunction with one another, paint a positive picture of the CCMT and its value within an academic engineering design context. The tool showed an ability to encourage student design teams to holistically explore the constraints of a design problem, negotiate a shared perspective, and communicate about future solution directions. The value of the tool went beyond that, however, as it allowed students to better understand constraint interactions and anticipate their effects on their particular design processes. As a result, the CCMT even showed potential benefits with respect the quality of design outcomes. The results of this study show great promise for the tool to be leveraged within academic engineering design contexts, but also indicate its potential value in other academic and practical contexts as well.

Chapter 8: Conclusion

Viewing products and design processes in light of complexity theory requires that designers enlarge the system of interest beyond the confines of the artifact to include an understanding of the *entire* artifact system. Whether talking about form and context, the artifact and the activity, the design and the user, or the organism and its environment, it is critical to recognize that the success, failure, or fitness of a designed artifact is dependent on factors that are larger than, and external to, the design itself. The interactions of countless individuals and organizations, searching for opportunities, defining design directions, competing, making purchasing decisions, applying designs, sharing ideas, and attempting to meet their own unique goals, work in concert with one another to create the emergent phenomena that we refer to as product systems and markets. Products, users, cultures, and designers all interact in highly complex, non-linear ways, leading to significant challenges engendered by the decomposition of design problems, managing constraint interactions, balancing trade-offs across perspectives, and changing in step with the surrounding world.

Because of the multitude of interactions and ever–greater amounts of information, designers are forced to focus on smaller, more manageable parts of the system in order to manage their own limited perspective. But designers must also broaden their understanding of the design problem to include the many perspectives that exist throughout the larger product system. Although inherently incomplete, each perspective within a product system—whether designer, manufacturer, marketer, stockholder, service personnel, or user—offers indispensable knowledge and insight. The question of how to effectively balance these perspectives in the face of limited resources is both an unsolvable problem and an unavoidable fact of design. The goal of design, then, is to identify and frame problems with the intention of introducing artifacts that take on meaning and relevance for a particular application within the actual context of use.

Through the execution of a design process, problems are defined, designs are developed, and designs become embodied in physical artifacts. These artifacts come into being at a

particular point in time, under a particular set of circumstances, in order to meet a particular set of needs. Upon its introduction into the world, designs shift and grow alongside users, patterns of use, and contexts, meeting unforeseen needs and creating new constraints and opportunities along the way. Eventually, when a design fails to serve its purpose or another design is perceived to better fit the users' context, the artifact is re-designed or replaced. Over time, artifacts shape stakeholders' understandings, tasks, goals, and aspirations, along with the intended field of activity, just as those pieces of the system shape future designs. This is the essence of a co-evolutionary system, and is central to what makes design challenging to do, and to study: artifacts are simultaneously responses to, and creators of, new constraints, problems, and opportunities.

The influence of the designer plays out within this context, as designers are tasked to identify opportunities, solve problems, and balance constraints. While it is not possible to fully predict or control the evolution of complex product systems, designers can endeavor to better understand the structures and entities that drive complex artifact systems. Doing so can help to ensure design solutions that are more closely aligned to systems in which they exist, thereby increasing the likelihood of developing products that fulfill actual needs, create innovative opportunities, and circumvent potentially avoidable failures.

As a result of complexity and change, real-world design processes are demanding and frequently messy processes. The successful completion of a design process relies on intuition and assumptions about how the world is changing, and its execution requires no small amount of personal skill and creativity from designers, engineers, and managers. Many existing design and research methods—ranging from House of Quality and Design Structure Matrix analysis to ethnographic research and participatory design methods—help designers in managing complexity and change within the design space. Every day, designers employ these strategies to design artifacts that will be meaningful and useful in a never–fully–defined context and an uncertain future. The inaccessibility of the complexity that underlies these problems, however, has largely limited the discourse on design to focusing on specific applications, case studies, methods, and stories.

Viewing design as a transformative activity within a larger complex product system transcends the traditional view of design problems. Doing so does not, however, advocate a new class of design problem, specific categorizations, or any single solution method; rather, it is a new perspective from which to view all design activity. This view establishes a fundamentally

different set of challenges for designers, educators, and design organizations. It is a view that, in many ways, positions solutions as a secondary result that can only emerge after first understanding the more central aspects of the design problem, its context, and the underlying constraints. Framed in this way, design problems demand a new approach: one which requires shifting perspectives, drawing new boundaries, never-ending exploration, negotiating a shared problem definition amongst multiple stakeholders, and developing a detailed understanding of a more complete set of design constraints.

This dissertation has confronted the challenges of complexity within design by developing an original synthesis based upon literature from the diverse fields of complexity science, evolutionary biology, industrial design, and engineering. It is intended to help designers of all types to transition from an understanding of specific design situations to a more general understanding characterized by the patterns, structure, and phenomena that govern all complex systems. This has primarily been accomplished by increasing the accessibility of complexity through the development of the constraint framework, and the implementation of the concurrent constraint management tool.

In an effort to make complexity *more conceptually accessible* this dissertation has introduced a constraint framework comprised of five primary categories: physical, technological, market, socio-cultural, and use. This constraint framework provides a scaffold for understanding, exploring, and discussing the constraints (and constraint interactions) that underlie real-world design problems. This is important as the constraints on a design problem exert a profound influence on the processes and methods used to generate relevant design knowledge. Everything from broad and well-established design standards to problem specific design research is in some way constrained by factors related to the context of creation and adoption. In this way, constraints shape the artifact itself as well as the knowledge and skill that conditions the artifact's creation. The constraint framework has also been structured to present a view of the design problem that is representative of the challenges that actually exist within the design space, while still being accessible to designers, teams, and organizations. It is not intended as an exhaustive set, but rather helps designers to manage their own perspectives and track the constraints that structure and propel the design process.

While the constraint framework helps designers to structure thinking and discourse with respect to a design problem and context, it does little to actually encourage its use, direct

cognitive activity, or aid in the process of actually designing an artifact—it helps designers to better understand the complexity of the world, not to manage it. To that end, the concurrent constraint management tool (CCMT) was developed as one possible method to help designers, educators, and students define the design space and manage complex constraint interactions within the design process. The CCMT, in this way, helps to make the complexity of design processes and systems *more practically accessible*. It provides a useful tool through which design teams can explore relevant constraints, shift perspectives, assess alternative directions, negotiate a shared understanding of the problem, manage trade-offs, anticipate changes in the design context, and better foresee the future effects of design decisions.

When deployed in a two-part research study the CCMT showed encouraging statistical results with respect to teamwork, the design team's ability to negotiate a shared view of the problem, their understanding of relevant factors, students' perceptions of the tool, and (to some degree) the quality of their final design solutions. These results were directly supported by qualitative feedback gathered during a second study intended to assess the tool along dimensions not previously possible. Still, like every designed artifact the CCMT is an attempt to simultaneously address a myriad of often competing constraints. Accordingly, its initial introduction into an actual context of use represented a significant opportunity for learning about the design of the tool, as well as our current view of the design problem and the underlying constraint space.

There is potential for the tool to be expanded along a number of possible avenues ranging from a more polished Excel program or a fully featured piece of stand-alone software, to a web-based collaborative tool or a re-imagined visual tool built upon the foundations established by the CCMT (a sort of "CCMT-light," if you will). Improvements to the tool's usability and its visual presentation are two aspects of the tool that were frequently recognized as future opportunities. Additionally, ways to increase the informational content of the tool, better direct designers to establish constraints and interactions at an appropriate pace, and reduce the ambiguity of evaluations may all further increase its utility.

Introducing the CCMT into an academic design context answered many questions about the tool's validity and the ways in which design teams deal with (and struggle to deal with) the complexity of real-world design challenges. At the same time, the positive returns from the CCMT research also created a number of new research questions, and paved the way for

potentially valuable future research. Extensive study needs to be completed in order to confirm the reproducibility of the CCMT's usefulness across other design processes and contexts. Currently planned efforts to more fully integrate the CCMT into the instruction of an engineering product design course and an engineering product design capstone at the Ohio State University should provide ample opportunity for this, as well as increased opportunities for qualitative feedback. If positive results continue to be shown in these contexts, the CCMT can then be deployed and measured (along dimensions similar to those measured in the previous study) for projects with larger scopes that better approximate a 'complete' design process. Initially, these expanded results may be found by deploying the tool within the context of graduate research projects and other undergraduate courses from within other academic departments and design contexts. Further positive results in these contexts will eventually justify the tool being deployed in industry product design processes that are more characterized by multiple perspectives, trade-offs, and intense resource pressures.

Taking a step back to view the wide-ranging topics of this dissertation reveals strong connections between what might have initially appeared as disparate parts. A better understanding of the core concepts, structures, and phenomenon of complex systems became the basis for the creation of the constraint framework. And the concurrent constraint matrix would not exist if it were not for examining the constraint framework in light of the previously explored complexity concepts, management strategies, and an emerging understanding of design as an adaptive process. At the same time, the success and promise of the CCMT's deployment evidences the need of design teams to better manage complexity, and helps to validate the constraint framework.

Utilized in tandem, the constraint framework and the concurrent constraint matrix can increase the conceptual and practical accessibility of the complexity that underlies every product design process. If used appropriately, these methods provide a platform for understanding, exploration, and design that can help designers of all types to develop solutions that are better aligned to the constraint environment that characterizes their unique design contexts. Finding application for these concepts and tools is all about helping designers and organizations to conduct research, design, and product management in ways that will extend their ability to see the world around them as it actually exists, strengthen their ability to identify unmet needs and desires, appropriately balance difficult trade-offs, and increase their foresight about how to move

into an uncertain future. In turn, this promotes the development of innovative products that can be better maintained in the face of a constantly changing design environment.

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Appendix A: Concurrent Constraint Matrix Excel Code

Excel Code (Windows)

```
VERSION 1.0 CLASS
BEGIN
  MultiUse = -1  'True
END

Attribute VB_Name = "Sheet1"
Attribute VB_GlobalNameSpace = False
Attribute VB_Creatable = False
Attribute VB_PredeclaredId = True
Attribute VB_Exposed = True
Public OldRowCount As Long
Public OldColumnCount As Long
Public running As Boolean

Public Function symetricMatrixNameColumn() As Integer
    symetricMatrixNameColumn = 2
End Function

Public Function symetricMatrixStakeholderColumn() As Integer
    symetricMatrixStakeholderColumn = 3
End Function

Public Function symetricMatrixWeightColumn() As Integer
    symetricMatrixWeightColumn = 4
End Function

Public Function symetricMatrixDeltaColumn() As Integer
    symetricMatrixDeltaColumn = 5
End Function

Public Function symetricMatrixPosInteractionColumn() As Integer
    symetricMatrixPosInteractionColumn = 6
End Function

Public Function symetricMatrixNegInteractionColumn() As Integer
    symetricMatrixNegInteractionColumn = 7
End Function

Public Function symetricMatrixTotInteractionColumn() As Integer
    symetricMatrixTotInteractionColumn = 8
End Function

Public Function symetricMatrixSubsectionLabelRow() As Integer
    symetricMatrixSubsectionLabelRow = 6
End Function

Public Function symetricMatrixItemCount() As Integer
    symetricMatrixItemCount = WorksheetFunction.CountA(Range("B7:B57"))
End Function

Public Function symetricMatrixRange() As Range
    Set symetricMatrixRange = Range("I7").Resize(symetricMatrixItemCount, symetricMatrixItemCount)
End Function

Public Function categoryHighlightColumnRange() As Range
    Set categoryHighlightColumnRange = Range("A6").Resize(1, symetricMatrixItemCount - symetricMatrixRowOffset + 1)
End Function
```

```
Public Function categoryHighlightRowRange() As Range
   Set categoryHighlightRowRange = Range("A6").Resize(symetricMatrixItemCount + 1, 1)
End Function

Public Function categoryNameColumnRange() As Range
   Set categoryNameColumnRange = Range("B7").Resize(symetricMatrixItemCount, 4)
End Function

Public Function categoryStakeholderColumnRange() As Range
   Set categoryStakeholderColumnRange = Range("C7").Resize(symetricMatrixItemCount, 1)
End Function

Public Function stakeholderItemCount() As Integer
   stakeholderItemCount = WorksheetFunction.CountA(Sheet3.Range("A2:B57"))
End Function

Public Function stakeholderColumnRange() As Range
   Set stakeholderColumnRange = Sheet3.Range("A2").Resize(stakeholderItemCount, 1)
End Function

Public Function buildStakeholderListView() As Boolean
   Sheet1.ListBox1.Clear
   Dim itr As Integer
   itr = 1
   For Each Cell In stakeholderColumnRange.Cells
      Sheet1.ListBox1.AddItem (Cell.Text)
      itr = itr + 1
   Next
End Function

Public Function inCategoryHighlightColumnRange(testRange As Range) As Boolean
   Dim InterSectRange As Range
   Set InterSectRange = Application.Intersect(testRange, categoryHighlightColumnRange)
   inCategoryHighlightColumnRange = Not InterSectRange Is Nothing
   Set InterSectRange = Nothing
End Function

Public Function inCategoryHighlightRowRange(testRange As Range) As Boolean
   Dim InterSectRange As Range
   Set InterSectRange = Application.Intersect(testRange, categoryHighlightRowRange)
   inCategoryHighlightRowRange = Not InterSectRange Is Nothing
   Set InterSectRange = Nothing
End Function

Public Function inCategoryNameColumnRange(testRange As Range) As Boolean
   Dim InterSectRange As Range
   Set InterSectRange = Application.Intersect(testRange, categoryNameColumnRange)
   inCategoryNameColumnRange = Not InterSectRange Is Nothing
   Set InterSectRange = Nothing
End Function

Public Function symetricMatrixColumnOrigin() As Integer
   symetricMatrixColumnOrigin = symetricMatrixRange.column
End Function

Public Function symetricMatrixRowOrigin() As Integer
   symetricMatrixRowOrigin = symetricMatrixRange.row
End Function
```

```
Public Function symetricMatrixColumnOffset() As Integer
    symetricMatrixColumnOffset = -5
End Function

Public Function symetricMatrixRowOffset() As Integer
    symetricMatrixRowOffset = -7
End Function

Public Function highlightStakeholderWithValue(value As Integer)
  For Each Cell In categoryStakeholderColumnRange.Cells
    Dim exists As Boolean
    Dim positon As Integer
    Dim cellText As String
    Dim compareText As String
    cellText = Cell.Text
    compareText = Replace(Str(value), " ", "")
    positon = InStr(cellText, compareText)
    exists = InStr(cellText, compareText) <> 0
    If exists Then
      Cell.Interior.ColorIndex = 54
    End If
  Next
End Function

Public Function highlightStakeholders() As Boolean
  For i = 0 To Sheet1.ListBox1.ListCount - 1
    If Sheet1.ListBox1.Selected(i) = True Then
      highlightStakeholderWithValue (i + 1)
    End If
  Next
End Function

Public Function highlightMatrixRowWithColor(row As Range, color As Long, continue As Boolean) As Boolean
  If continue = True Then
    For Each Cell In Application.Intersect(row, symetricMatrixRange).Cells
      If (Cell.value > symetricMatrixHighlightThreshold) Or (Cell.value > symetricMatrixHighlightThreshold) Then
        Dim finished As Boolean
        finished = highlightMatrixRowWithColor(row.Offset((Cell.column - symetricMatrixRange.column) - (Cell.row -
symetricMatrixRange.row), 0), 36, False)
      End If
    Next
    For Each Cell In symetricMatrixRange.Cells
      If ((Cell.value > symetricMatrixHighlightThreshold) And (Cell.row = row.row)) Or ((Cell.value >
symetricMatrixHighlightThreshold) And ((Cell.column + symetricMatrixRowOffset) = row.row +
symetricMatrixColumnOffset)) Then
        Cell.Interior.ColorIndex = color
        Cells(Cell.row, symetricMatrixNameColumn).Interior.ColorIndex = color
      End If
    Next
  Else
    For Each Cell In symetricMatrixRange.Cells
      If ((Cell.value > symetricMatrixHighlightThreshold) And (Cell.row = row.row)) Or ((Cell.value >
symetricMatrixHighlightThreshold) And ((Cell.column + symetricMatrixRowOffset) = row.row +
symetricMatrixColumnOffset)) Then
        Cell.Interior.ColorIndex = color

        Cells(Cell.row, symetricMatrixNameColumn).Interior.ColorIndex = color
      End If
    Next
  End If
```

```
End Function

Public Function highlightNegMatrixRowWithColor(row As Range, color As Long, continue As Boolean) As Boolean
   If continue = True Then
      For Each Cell In Application.Intersect(row, symetricMatrixRange).Cells
         Dim finished As Boolean
         If (Cell.value < symetricMatrixNegHighlightThreshold) Or (Cell.value < symetricMatrixNegHighlightThreshold)
Then
            finished = highlightNegMatrixRowWithColor(row.Offset((Cell.column - symetricMatrixRange.column) -
(Cell.row - symetricMatrixRange.row), 0), 38, False)
         End If
      Next
      For Each Cell In symetricMatrixRange.Cells
         If ((Cell.value < symetricMatrixNegHighlightThreshold) And (Cell.row = row.row)) Or ((Cell.value <
symetricMatrixNegHighlightThreshold) And ((Cell.column + symetricMatrixRowOffset) = row.row +
symetricMatrixColumnOffset)) Then
            Cell.Interior.ColorIndex = color
            Cells(Cell.row, symetricMatrixNameColumn).Interior.ColorIndex = color
         End If
      Next
   Else
      For Each Cell In symetricMatrixRange.Cells
         If ((Cell.value < symetricMatrixNegHighlightThreshold) And (Cell.row = row.row)) Or ((Cell.value <
symetricMatrixNegHighlightThreshold) And ((Cell.column + symetricMatrixRowOffset) = row.row +
symetricMatrixColumnOffset)) Then
            Cell.Interior.ColorIndex = color
            Cells(Cell.row, symetricMatrixNameColumn).Interior.ColorIndex = color
         End If
      Next
   End If
End Function

Public Function symetricMatrixHighlightThreshold() As Integer
   symetricMatrixHighlightThreshold = Cells(5, 6) - 1
End Function

Public Function symetricMatrixHighlightDepth() As Integer
   symetricMatrixHighlightDepth = Cells(4, 6)
End Function

Public Function symetricMatrixNegHighlightThreshold() As Integer
   symetricMatrixNegHighlightThreshold = Cells(3, 6) + 1
End Function

Public Function symetricMatrixNegHighlightDepth() As Integer
   symetricMatrixNegHighlightDepth = Cells(2, 6)
End Function

Public Function inSymetricMatricRange(testRange As Range) As Boolean
   inSymetricMatricRange = Not Application.Intersect(testRange, symetricMatrixRange) Is Nothing
End Function

Private Sub Worksheet_Change(ByVal Target As Range)
   If Not running Then
      running = True
      Dim column As Integer
      If UsedRange.Rows.Count > OldRowCount And Target.Count > 1 Then
         column = Target.row + 2
         Columns(column).Insert
      ElseIf UsedRange.Rows.Count < OldRowCount And Target.Count > 1 Then
```

```
            column = Target.row + 2
            Columns(column).EntireColumn.Delete
        ElseIf UsedRange.Columns.Count > OldColumnCount Then
            column = Target.row - 1
        Else
            If inSymetricMatricRange(Target) Then
                Cells(Target.column + symetricMatrixRowOffset - symetricMatrixColumnOffset, Target.row -
symetricMatrixRowOffset + symetricMatrixColumnOffset) = Cells(Target.row, Target.column)
                Cells(Target.row, symetricMatrixPosInteractionColumn) =
WorksheetFunction.SumIf(Application.Intersect(Target.EntireRow, symetricMatrixRange), ">0")
                Cells(Target.column + symetricMatrixRowOffset - symetricMatrixColumnOffset,
symetricMatrixPosInteractionColumn) = WorksheetFunction.SumIf(Application.Intersect(Target.EntireColumn,
symetricMatrixRange), ">0")
                Cells(Target.row, symetricMatrixNegInteractionColumn) =
WorksheetFunction.SumIf(Application.Intersect(Target.EntireRow, symetricMatrixRange), "<0")
                Cells(Target.column + symetricMatrixRowOffset - symetricMatrixColumnOffset,
symetricMatrixNegInteractionColumn) = WorksheetFunction.SumIf(Application.Intersect(Target.EntireColumn,
symetricMatrixRange), "<0")
                Cells(Target.row, symetricMatrixTotInteractionColumn) =
WorksheetFunction.CountIf(Application.Intersect(Target.EntireRow, symetricMatrixRange), ">0") +
WorksheetFunction.CountIf(Application.Intersect(Target.EntireRow, symetricMatrixRange), "<0")
                Cells(Target.column + symetricMatrixRowOffset - symetricMatrixColumnOffset,
symetricMatrixTotInteractionColumn) = WorksheetFunction.CountIf(Application.Intersect(Target.EntireColumn,
symetricMatrixRange), ">0") + WorksheetFunction.CountIf(Application.Intersect(Target.EntireColumn,
symetricMatrixRange), "<0")
            End If
            If Target.column = 1 Then
                Cells(6, Target.row + 2) = Cells(Target.row, Target.column)
            End If
            If Cells(4, 6).value > 2 Then
                Cells(4, 6) = 2
            ElseIf Cells(4, 6).value < 1 Then
                Cells(4, 6) = 1
            End If
            If Cells(2, 6).value > 2 Then
                Cells(2, 6) = 2
            ElseIf Cells(2, 6).value < 1 Then
                Cells(2, 6) = 1
            End If
        End If
        OldRowCount = UsedRange.Rows.Count
        OldColumnCount = UsedRange.Columns.Count
        running = False
    End If
End Sub

Private Sub Worksheet_SelectionChange(ByVal Target As Range)
    OldRowCount = UsedRange.Rows.Count
    OldColumnCount = UsedRange.Columns.Count
    If (Target.row = 1) And (Target.column = 4) Then
        Dim buildComplete As Boolean
        buildComplete = buildStakeholderListView
    End If
    If Not ((Target.Rows.Count > 1) Or (Target.Columns.Count > 1)) Then
        Cells.Interior.ColorIndex = xlColorIndexNone
        Dim finished As Boolean
        Dim continue As Boolean
        continue = symetricMatrixHighlightDepth > 1
        finished = highlightStakeholders()
        Cells(6, symetricMatrixStakeholderColumn).Interior.ColorIndex = 35
```

```
        Cells(6, symetricMatrixWeightColumn).Interior.ColorIndex = 38
        Cells(6, symetricMatrixDeltaColumn).Interior.ColorIndex = 40
        If inSymetricMatricRange(Target) Then
            finished = highlightMatrixRowWithColor(Target.EntireRow, 44, continue)
            finished = highlightNegMatrixRowWithColor(Target.EntireRow, 7, continue)
            Cells(Target.row, symetricMatrixNameColumn).Interior.ColorIndex = 33
            Cells(Target.row, symetricMatrixStakeholderColumn).Interior.ColorIndex = 33
            Cells(Target.row, symetricMatrixWeightColumn).Interior.ColorIndex = 33
            Cells(Target.row, symetricMatrixDeltaColumn).Interior.ColorIndex = 33
            Cells(Target.row, symetricMatrixPosInteractionColumn).Interior.ColorIndex = 33
            Cells(Target.row, symetricMatrixNegInteractionColumn).Interior.ColorIndex = 33
            Cells(Target.row, symetricMatrixTotInteractionColumn).Interior.ColorIndex = 33
            Cells(Target.row, 1).Interior.ColorIndex = 33
            Cells(symetricMatrixSubsectionLabelRow, Target.column).Interior.ColorIndex = 33
        End If
        If inCategoryNameColumnRange(Target) Then
            finished = highlightMatrixRowWithColor(Target.EntireRow, 44, continue)
            finished = highlightNegMatrixRowWithColor(Target.EntireRow, 7, continue)
            Cells(Target.row, symetricMatrixNameColumn).Interior.ColorIndex = 33
            Cells(Target.row, symetricMatrixStakeholderColumn).Interior.ColorIndex = 33
            Cells(Target.row, symetricMatrixWeightColumn).Interior.ColorIndex = 33
            Cells(Target.row, symetricMatrixDeltaColumn).Interior.ColorIndex = 33
            Cells(Target.row, symetricMatrixPosInteractionColumn).Interior.ColorIndex = 33
            Cells(Target.row, symetricMatrixNegInteractionColumn).Interior.ColorIndex = 33
            Cells(Target.row, symetricMatrixTotInteractionColumn).Interior.ColorIndex = 33
            Cells(Target.row, 1).Interior.ColorIndex = 33
        End If
        For Each Cell In symetricMatrixRange.Cells
            If (Cell.row - symetricMatrixRowOffset) = (Cell.column - symetricMatrixColumnOffset) Then
                Cell.Interior.ColorIndex = 15
            End If
        Next
        For Each Cell In categoryHighlightRowRange.Cells
            If Cell.value = "" Then
                Application.Intersect(Cell.EntireRow, symetricMatrixRange).Interior.ColorIndex = 16
                Cells(Cell.row, symetricMatrixNameColumn).Interior.ColorIndex = 16
                Cells(Cell.row, symetricMatrixStakeholderColumn).Interior.ColorIndex = 16
                Cells(Cell.row, symetricMatrixWeightColumn).Interior.ColorIndex = 16
                Cells(Cell.row, symetricMatrixDeltaColumn).Interior.ColorIndex = 16
                Cells(Cell.row, symetricMatrixPosInteractionColumn).Interior.ColorIndex = 16
                Cells(Cell.row, symetricMatrixNegInteractionColumn).Interior.ColorIndex = 16
                Cells(Cell.row, symetricMatrixTotInteractionColumn).Interior.ColorIndex = 16
                Cells(Cell.row, 1).Interior.ColorIndex = 16
            End If
        Next
        For Each Cell In categoryHighlightColumnRange.Cells
            If Cell.value = "" Then
                Application.Intersect(Cell.EntireColumn, symetricMatrixRange).Interior.ColorIndex = 16
            End If
        Next
    End If
End Sub

Sub ListBox1_Change()
    Dim finished As Boolean
    finished = highlightStakeholders()
End Sub
```

Excel Code (OSX)

```
VERSION 1.0 CLASS
BEGIN
  MultiUse = -1  'True
END

Attribute VB_Name = "Sheet1"
Attribute VB_GlobalNameSpace = False
Attribute VB_Creatable = False
Attribute VB_PredeclaredId = True
Attribute VB_Exposed = True
Public OldRowCount As Long
Public OldColumnCount As Long
Public running As Boolean

Public Function symetricMatrixNameColumn() As Integer
    symetricMatrixNameColumn = 2
End Function

Public Function symetricMatrixStakeholderColumn() As Integer
    symetricMatrixStakeholderColumn = 3
End Function

Public Function symetricMatrixWeightColumn() As Integer
    symetricMatrixWeightColumn = 4
End Function

Public Function symetricMatrixDeltaColumn() As Integer
    symetricMatrixDeltaColumn = 5
End Function

Public Function symetricMatrixPosInteractionColumn() As Integer
    symetricMatrixPosInteractionColumn = 6
End Function

Public Function symetricMatrixNegInteractionColumn() As Integer
    symetricMatrixNegInteractionColumn = 7
End Function

Public Function symetricMatrixTotInteractionColumn() As Integer
    symetricMatrixTotInteractionColumn = 8
End Function

Public Function symetricMatrixSubsectionLabelRow() As Integer
    symetricMatrixSubsectionLabelRow = 6
End Function

Public Function symetricMatrixItemCount() As Integer
    symetricMatrixItemCount = WorksheetFunction.CountA(Range("B7:B57"))
End Function

Public Function symetricMatrixRange() As Range
    Set symetricMatrixRange = Range("I7").Resize(symetricMatrixItemCount, symetricMatrixItemCount)
End Function

Public Function categoryHighlightColumnRange() As Range
    Set categoryHighlightColumnRange = Range("A6").Resize(1, symetricMatrixItemCount - symetricMatrixRowOffset + 1)
End Function
```

```
Public Function categoryHighlightRowRange() As Range
    Set categoryHighlightRowRange = Range("A6").Resize(symetricMatrixItemCount + 1, 1)
End Function

Public Function categoryNameColumnRange() As Range
    Set categoryNameColumnRange = Range("B7").Resize(symetricMatrixItemCount, 4)
End Function

Public Function categoryStakeholderColumnRange() As Range
    Set categoryStakeholderColumnRange = Range("C7").Resize(symetricMatrixItemCount, 1)
End Function

Public Function stakeholderItemCount() As Integer
    stakeholderItemCount = WorksheetFunction.CountA(Sheet3.Range("A2:B57"))
End Function

Public Function stakeholderColumnRange() As Range
    Set stakeholderColumnRange = Sheet3.Range("A2").Resize(stakeholderItemCount, 1)
End Function

Public Function inCategoryHighlightColumnRange(testRange As Range) As Boolean
    Dim InterSectRange As Range
    Set InterSectRange = Application.Intersect(testRange, categoryHighlightColumnRange)
    inCategoryHighlightColumnRange = Not InterSectRange Is Nothing
    Set InterSectRange = Nothing
End Function

Public Function inCategoryHighlightRowRange(testRange As Range) As Boolean
    Dim InterSectRange As Range
    Set InterSectRange = Application.Intersect(testRange, categoryHighlightRowRange)
    inCategoryHighlightRowRange = Not InterSectRange Is Nothing
    Set InterSectRange = Nothing
End Function

Public Function inCategoryNameColumnRange(testRange As Range) As Boolean
    Dim InterSectRange As Range
    Set InterSectRange = Application.Intersect(testRange, categoryNameColumnRange)
    inCategoryNameColumnRange = Not InterSectRange Is Nothing
    Set InterSectRange = Nothing
End Function

Public Function symetricMatrixColumnOrigin() As Integer
    symetricMatrixColumnOrigin = symetricMatrixRange.column
End Function

Public Function symetricMatrixRowOrigin() As Integer
    symetricMatrixRowOrigin = symetricMatrixRange.row
End Function

Public Function symetricMatrixColumnOffset() As Integer
        symetricMatrixColumnOffset = -5
End Function

Public Function symetricMatrixRowOffset() As Integer
        symetricMatrixRowOffset = -7
End Function

Public Function highlightMatrixRowWithColor(row As Range, color As Long, continue As Boolean) As Boolean
    If continue = True Then
```

```
      For Each Cell In Application.Intersect(row, symetricMatrixRange).Cells
         If (Cell.value > symetricMatrixHighlightThreshold) Or (Cell.value > symetricMatrixHighlightThreshold) Then
            Dim finished As Boolean
            finished = highlightMatrixRowWithColor(row.Offset((Cell.column - symetricMatrixRange.column) - (Cell.row -
symetricMatrixRange.row), 0), 36, False)
         End If
      Next
      For Each Cell In symetricMatrixRange.Cells
         If ((Cell.value > symetricMatrixHighlightThreshold) And (Cell.row = row.row)) Or ((Cell.value >
symetricMatrixHighlightThreshold) And ((Cell.column + symetricMatrixRowOffset) = row.row +
symetricMatrixColumnOffset)) Then
            Cell.Interior.ColorIndex = color
            Cells(Cell.row, symetricMatrixNameColumn).Interior.ColorIndex = color
         End If
      Next
   Else
      For Each Cell In symetricMatrixRange.Cells
         If ((Cell.value > symetricMatrixHighlightThreshold) And (Cell.row = row.row)) Or ((Cell.value >
symetricMatrixHighlightThreshold) And ((Cell.column + symetricMatrixRowOffset) = row.row +
symetricMatrixColumnOffset)) Then
            Cell.Interior.ColorIndex = color
            Cells(Cell.row, symetricMatrixNameColumn).Interior.ColorIndex = color
         End If
      Next
   End If
End Function

Public Function highlightNegMatrixRowWithColor(row As Range, color As Long, continue As Boolean) As Boolean
   If continue = True Then
      For Each Cell In Application.Intersect(row, symetricMatrixRange).Cells
         Dim finished As Boolean
         If (Cell.value < symetricMatrixNegHighlightThreshold) Or (Cell.value < symetricMatrixNegHighlightThreshold)
Then
            finished = highlightNegMatrixRowWithColor(row.Offset((Cell.column - symetricMatrixRange.column) -
(Cell.row - symetricMatrixRange.row), 0), 38, False)
         End If
      Next
      For Each Cell In symetricMatrixRange.Cells
         If ((Cell.value < symetricMatrixNegHighlightThreshold) And (Cell.row = row.row)) Or ((Cell.value <
symetricMatrixNegHighlightThreshold) And ((Cell.column + symetricMatrixRowOffset) = row.row +
symetricMatrixColumnOffset)) Then
            Cell.Interior.ColorIndex = color
            Cells(Cell.row, symetricMatrixNameColumn).Interior.ColorIndex = color
         End If
      Next
   Else
      For Each Cell In symetricMatrixRange.Cells
         If ((Cell.value < symetricMatrixNegHighlightThreshold) And (Cell.row = row.row)) Or ((Cell.value <
symetricMatrixNegHighlightThreshold) And ((Cell.column + symetricMatrixRowOffset) = row.row +
symetricMatrixColumnOffset)) Then
            Cell.Interior.ColorIndex = color
            Cells(Cell.row, symetricMatrixNameColumn).Interior.ColorIndex = color
         End If
      Next
   End If
End Function

Public Function symetricMatrixHighlightThreshold() As Integer
   symetricMatrixHighlightThreshold = Cells(5, 6) - 1
End Function
```

```
Public Function symetricMatrixHighlightDepth() As Integer
   symetricMatrixHighlightDepth = Cells(4, 6)
End Function

Public Function symetricMatrixNegHighlightThreshold() As Integer
   symetricMatrixNegHighlightThreshold = Cells(3, 6) + 1
End Function

Public Function symetricMatrixNegHighlightDepth() As Integer
   symetricMatrixNegHighlightDepth = Cells(2, 6)
End Function

Public Function inSymetricMatricRange(testRange As Range) As Boolean
   inSymetricMatricRange = Not Application.Intersect(testRange, symetricMatrixRange) Is Nothing
End Function

Private Sub Worksheet_Change(ByVal Target As Range)
   If Not running Then
      running = True
      Dim column As Integer
      If UsedRange.Rows.Count > OldRowCount And Target.Count > 1 Then
         column = Target.row + 2
         Columns(column).Insert
      ElseIf UsedRange.Rows.Count < OldRowCount And Target.Count > 1 Then
         column = Target.row + 2
         Columns(column).EntireColumn.Delete
      ElseIf UsedRange.Columns.Count > OldColumnCount Then
         column = Target.row - 1
      Else
         If inSymetricMatricRange(Target) Then
            Cells(Target.column + symetricMatrixRowOffset - symetricMatrixColumnOffset, Target.row -
symetricMatrixRowOffset + symetricMatrixColumnOffset) = Cells(Target.row, Target.column)
            Cells(Target.row, symetricMatrixPosInteractionColumn) =
WorksheetFunction.SumIf(Application.Intersect(Target.EntireRow, symetricMatrixRange), ">0")
            Cells(Target.column + symetricMatrixRowOffset - symetricMatrixColumnOffset,
symetricMatrixPosInteractionColumn) = WorksheetFunction.SumIf(Application.Intersect(Target.EntireColumn,
symetricMatrixRange), ">0")
            Cells(Target.row, symetricMatrixNegInteractionColumn) =
WorksheetFunction.SumIf(Application.Intersect(Target.EntireRow, symetricMatrixRange), "<0")
            Cells(Target.column + symetricMatrixRowOffset - symetricMatrixColumnOffset,
symetricMatrixNegInteractionColumn) = WorksheetFunction.SumIf(Application.Intersect(Target.EntireColumn,
symetricMatrixRange), "<0")
            Cells(Target.row, symetricMatrixTotInteractionColumn) =
WorksheetFunction.CountIf(Application.Intersect(Target.EntireRow, symetricMatrixRange), ">0") +
WorksheetFunction.CountIf(Application.Intersect(Target.EntireRow, symetricMatrixRange), "<0")
            Cells(Target.column + symetricMatrixRowOffset - symetricMatrixColumnOffset,
symetricMatrixTotInteractionColumn) = WorksheetFunction.CountIf(Application.Intersect(Target.EntireColumn,
symetricMatrixRange), ">0") + WorksheetFunction.CountIf(Application.Intersect(Target.EntireColumn,
symetricMatrixRange), "<0")
         End If
         If Target.column = 1 Then
            Cells(6, Target.row + 2) = Cells(Target.row, Target.column)
         End If
         If Cells(4, 6).value > 2 Then
            Cells(4, 6) = 2
         ElseIf Cells(4, 6).value < 1 Then
            Cells(4, 6) = 1
         End If
         If Cells(2, 6).value > 2 Then
```

```
            Cells(2, 6) = 2
        ElseIf Cells(2, 6).value < 1 Then
            Cells(2, 6) = 1
        End If
    End If
    OldRowCount = UsedRange.Rows.Count
    OldColumnCount = UsedRange.Columns.Count
    running = False
  End If
End Sub

Private Sub Worksheet_SelectionChange(ByVal Target As Range)
  OldRowCount = UsedRange.Rows.Count
  OldColumnCount = UsedRange.Columns.Count
  If Not ((Target.Rows.Count > 1) Or (Target.Columns.Count > 1)) Then
    Cells.Interior.ColorIndex = xlColorIndexNone
    Dim finished As Boolean
    Dim continue As Boolean
    continue = symetricMatrixHighlightDepth > 1
    Cells(6, symetricMatrixStakeholderColumn).Interior.ColorIndex = 35
    Cells(6, symetricMatrixWeightColumn).Interior.ColorIndex = 38
    Cells(6, symetricMatrixDeltaColumn).Interior.ColorIndex = 40
    If inSymetricMatricRange(Target) Then
      finished = highlightMatrixRowWithColor(Target.EntireRow, 44, continue)
      finished = highlightNegMatrixRowWithColor(Target.EntireRow, 7, continue)
      Cells(Target.row, symetricMatrixNameColumn).Interior.ColorIndex = 33
      Cells(Target.row, symetricMatrixStakeholderColumn).Interior.ColorIndex = 33
      Cells(Target.row, symetricMatrixWeightColumn).Interior.ColorIndex = 33
      Cells(Target.row, symetricMatrixDeltaColumn).Interior.ColorIndex = 33
      Cells(Target.row, symetricMatrixPosInteractionColumn).Interior.ColorIndex = 33
      Cells(Target.row, symetricMatrixNegInteractionColumn).Interior.ColorIndex = 33
      Cells(Target.row, symetricMatrixTotInteractionColumn).Interior.ColorIndex = 33
      Cells(Target.row, 1).Interior.ColorIndex = 33
      Cells(symetricMatrixSubsectionLabelRow, Target.column).Interior.ColorIndex = 33
    End If
    If inCategoryNameColumnRange(Target) Then
      finished = highlightMatrixRowWithColor(Target.EntireRow, 44, continue)
      finished = highlightNegMatrixRowWithColor(Target.EntireRow, 7, continue)
      Cells(Target.row, symetricMatrixNameColumn).Interior.ColorIndex = 33
      Cells(Target.row, symetricMatrixStakeholderColumn).Interior.ColorIndex = 33
      Cells(Target.row, symetricMatrixWeightColumn).Interior.ColorIndex = 33
      Cells(Target.row, symetricMatrixDeltaColumn).Interior.ColorIndex = 33
      Cells(Target.row, symetricMatrixPosInteractionColumn).Interior.ColorIndex = 33
      Cells(Target.row, symetricMatrixNegInteractionColumn).Interior.ColorIndex = 33
      Cells(Target.row, symetricMatrixTotInteractionColumn).Interior.ColorIndex = 33
      Cells(Target.row, 1).Interior.ColorIndex = 33
    End If
    For Each Cell In symetricMatrixRange.Cells
      If (Cell.row - symetricMatrixRowOffset) = (Cell.column - symetricMatrixColumnOffset) Then
        Cell.Interior.ColorIndex = 15
      End If
    Next
    For Each Cell In categoryHighlightRowRange.Cells
      If Cell.value = "" Then
        Application.Intersect(Cell.EntireRow, symetricMatrixRange).Interior.ColorIndex = 16
        Cells(Cell.row, symetricMatrixNameColumn).Interior.ColorIndex = 16
        Cells(Cell.row, symetricMatrixStakeholderColumn).Interior.ColorIndex = 16
        Cells(Cell.row, symetricMatrixWeightColumn).Interior.ColorIndex = 16
        Cells(Cell.row, symetricMatrixDeltaColumn).Interior.ColorIndex = 16
        Cells(Cell.row, symetricMatrixPosInteractionColumn).Interior.ColorIndex = 16
```

```
            Cells(Cell.row, symetricMatrixNegInteractionColumn).Interior.ColorIndex = 16
            Cells(Cell.row, symetricMatrixTotInteractionColumn).Interior.ColorIndex = 16
            Cells(Cell.row, 1).Interior.ColorIndex = 16
          End If
        Next
        For Each Cell In categoryHighlightColumnRange.Cells
          If Cell.value = "" Then
            Application.Intersect(Cell.EntireColumn, symetricMatrixRange).Interior.ColorIndex = 16
          End If
        Next
      End If
End Sub
```

Appendix B: Student Surveys

Survey 1: Control

Please return before Monday Oct. 29th.

* Required

Your name: *

Please rate your current attitude about your design project. *

1 2 3 4 5

Most negative ○ ○ ○ ○ ○ Most positive

Please explain. *

Please rate your current attitude about the quality of your group's teamwork. *

1 2 3 4 5

Most negative ○ ○ ○ ○ ○ Most positive

Please explain. *

Please rate your current expectations about your team's design process. *

1 2 3 4 5

Most negative ○ ○ ○ ○ ○ Most positive

Please explain. *

Continued

Figure B.1: Control student survey 1, given near the outset of the project.

Figure B.1 Continued

Survey 1: Experimental

Please return before Monday Oct. 29th.

* Required

Your name: *

Please rate your current attitude about your design project. *

1 2 3 4 5

Most negative ○ ○ ○ ○ ○ Most positive

Please explain. *

Please rate your current attitude about the quality of your group's teamwork. *

1 2 3 4 5

Most negative ○ ○ ○ ○ ○ Most positive

Please explain. *

Please rate your current expectations about your team's design process. *

1 2 3 4 5

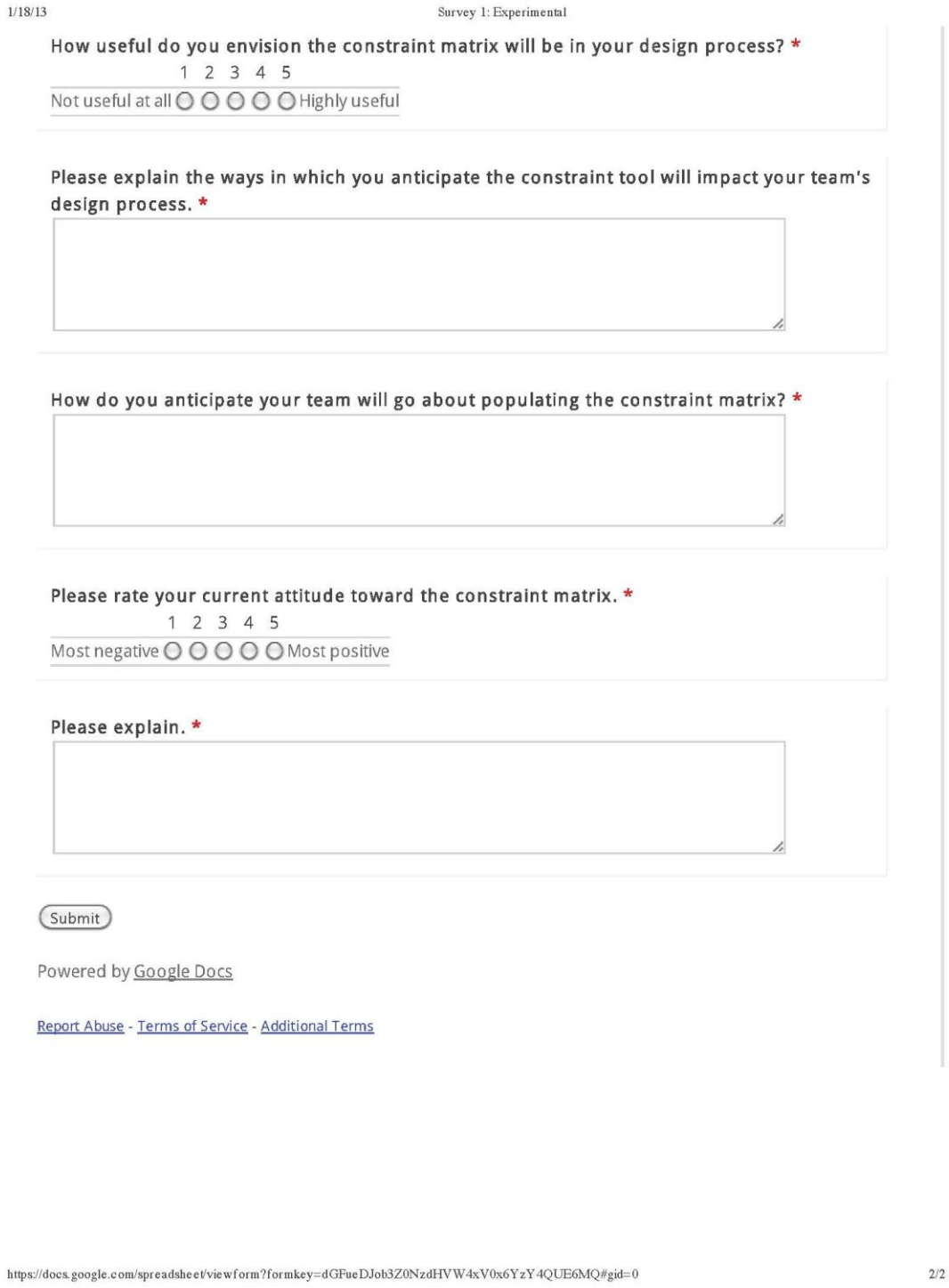
Most negative ○ ○ ○ ○ ○ Most positive

Please explain. *

Continued

Figure B.2: Experimental student survey 1, given near the outset of the project.

Figure B.2 continued



1/18/13 Survey 1: Experimental

How useful do you envision the constraint matrix will be in your design process? *

1 2 3 4 5

Not useful at all ○ ○ ○ ○ ○ Highly useful

Please explain the ways in which you anticipate the constraint tool will impact your team's design process. *

How do you anticipate your team will go about populating the constraint matrix? *

Please rate your current attitude toward the constraint matrix. *

1 2 3 4 5

Most negative ○ ○ ○ ○ ○ Most positive

Please explain. *

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https://docs.google.com/spreadsheet/viewform?formkey=dGFueDJob3Z0NzdHVW4xV0x6YzY4QUE6MQ#gid=0 2/2

Survey 2: Control form

Please return by Nov. 5th

* Required

Your name: *

Which constraint category (physical, technological, market, usage, socio-cultural) do you feel will be most important to the success of your design? *

Why? *

Please rate your current attitude about the quality of your group's teamwork. *

	1	2	3	4	5	
Most negative	○	○	○	○	○	Most positive

Please explain. *

Please rate the degree to which your team shares an understanding of the design problem, its relevant factors, and what needs to be done to successfully complete this project: *

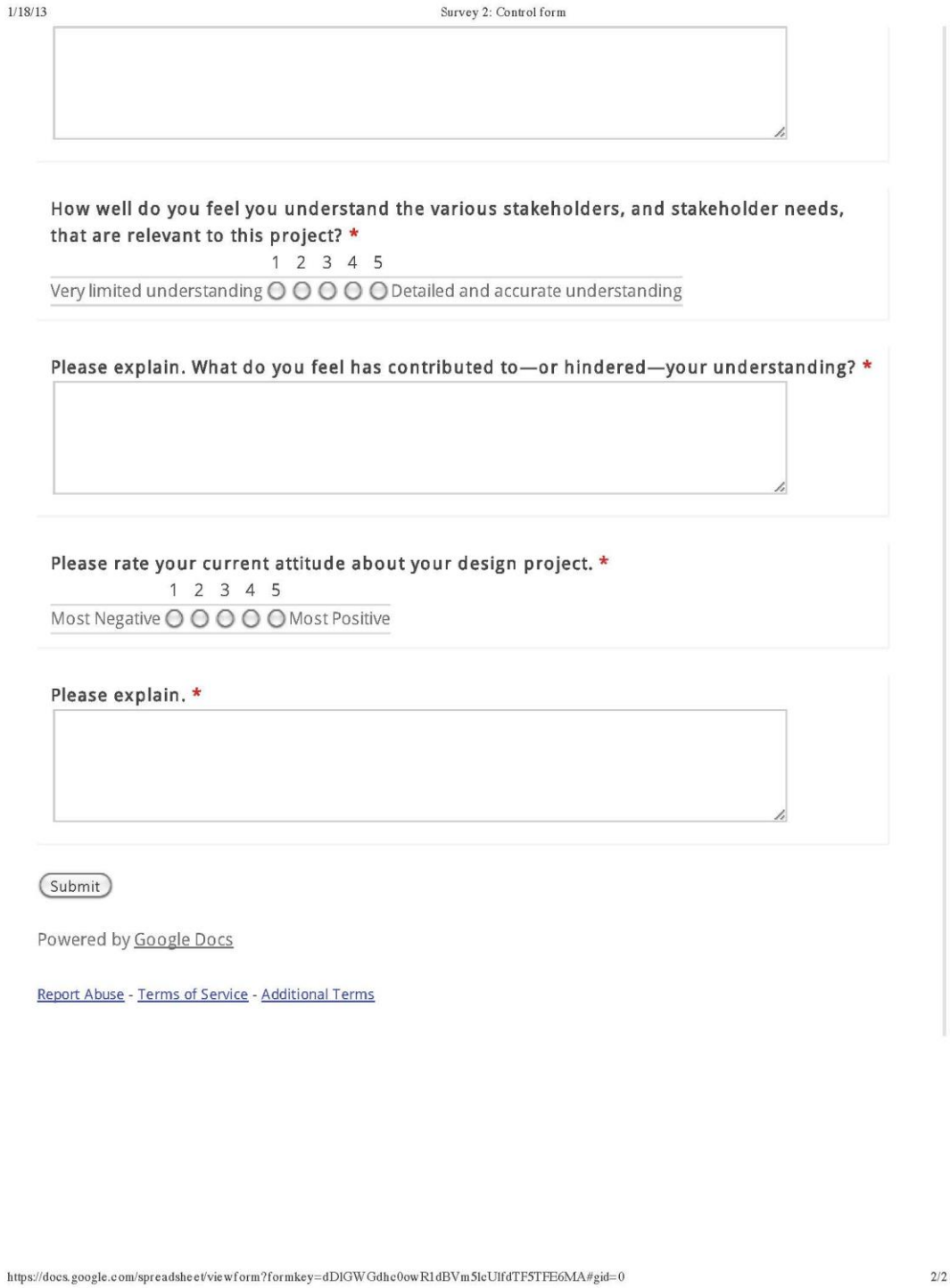
	1	2	3	4	5	
Totally different understanding	○	○	○	○	○	Completely shared understanding

Please explain. What do you feel has contributed to—or hindered—your groups' shared understanding? *

Continued

Figure B.3: Control student survey 2, given near the middle of the project.

Figure B.3 continued



Survey 2: Experimental form

Please return by Nov. 5th

* Required

Your name: *

Which constraint category (physical, technological, market, usage, socio-cultural) do you feel will be most important to the success of your design? *

Why? *

Please rate your current attitude about the quality of your group's teamwork. *

	1	2	3	4	5	
Most negative	○	○	○	○	○	Most positive

Please explain. *

Please rate the degree to which your team shares an understanding of the design problem, its relevant factors, and what needs to be done to successfully complete this project: *

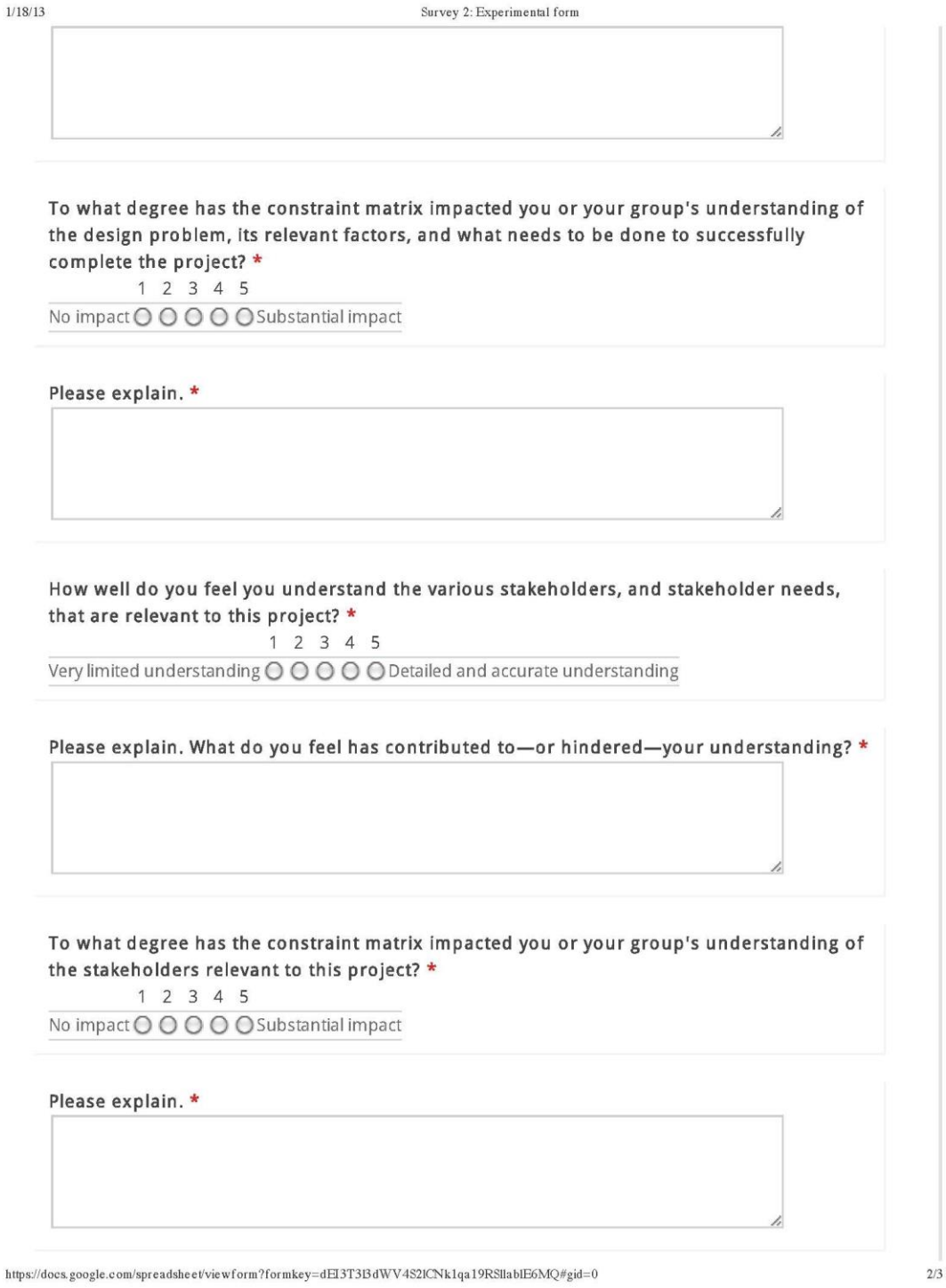
	1	2	3	4	5	
Totally different understanding	○	○	○	○	○	Completely shared understanding

Please explain. What do you feel has contributed to—or hindered—your groups' shared understanding? *

Continued

Figure B.4: Experimental student survey 2, given near the middle of the project.

Figure B.4 continued



1/18/13 Survey 2: Experimental form

To what degree has the constraint matrix impacted you or your group's understanding of the design problem, its relevant factors, and what needs to be done to successfully complete the project? *

1 2 3 4 5

No impact ○ ○ ○ ○ ○ Substantial impact

Please explain. *

How well do you feel you understand the various stakeholders, and stakeholder needs, that are relevant to this project? *

1 2 3 4 5

Very limited understanding ○ ○ ○ ○ ○ Detailed and accurate understanding

Please explain. What do you feel has contributed to—or hindered—your understanding? *

To what degree has the constraint matrix impacted you or your group's understanding of the stakeholders relevant to this project? *

1 2 3 4 5

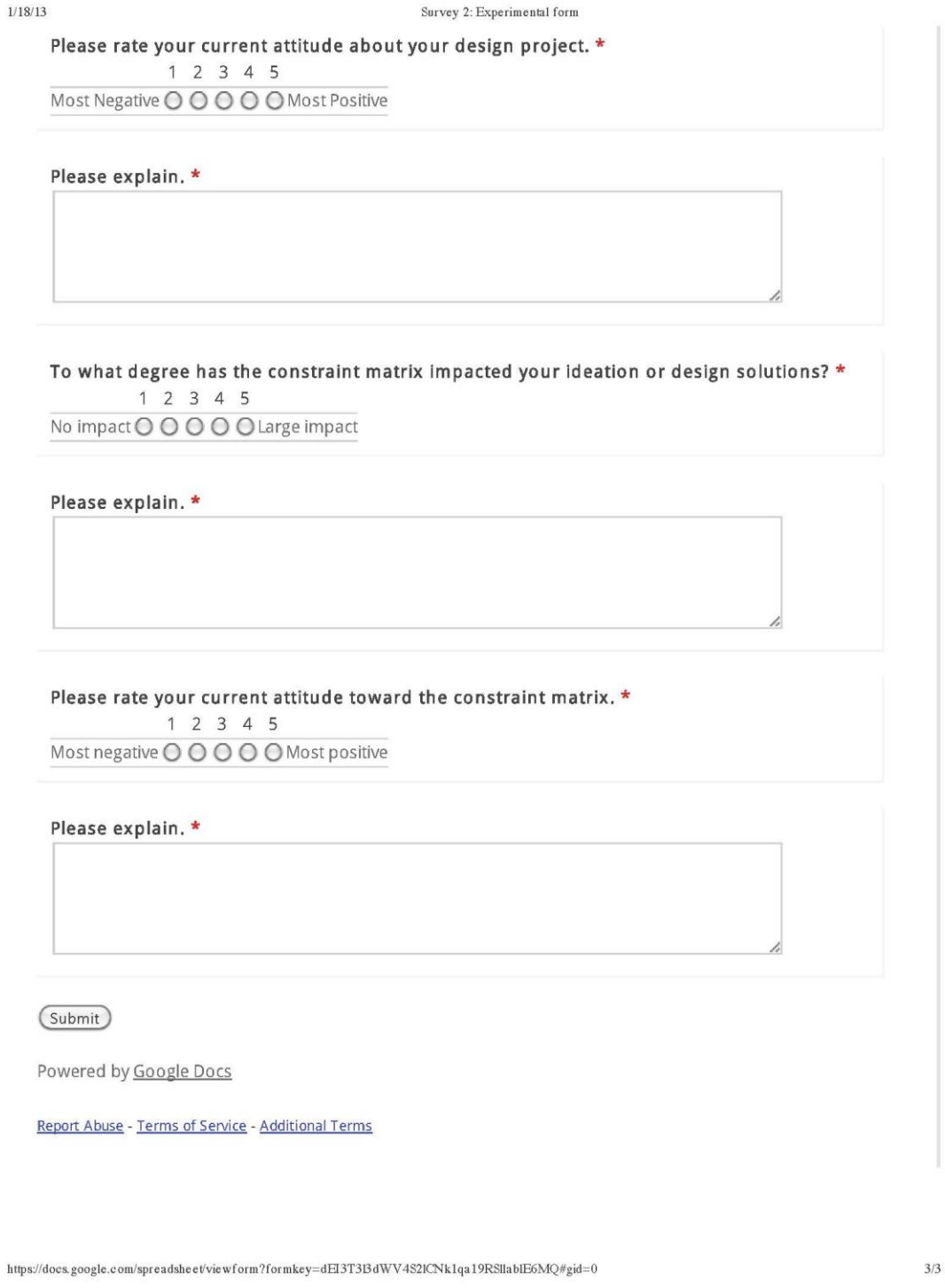
No impact ○ ○ ○ ○ ○ Substantial impact

Please explain. *

https://docs.google.com/spreadsheet/viewform?formkey=dEI3T3I3dWV4S2ICNk1qa19RSllabIE6MQ#gid=0 2/3

Continued

Figure B.4 continued



1/18/13 Survey 2: Experimental form

Please rate your current attitude about your design project. *

1 2 3 4 5

Most Negative ○ ○ ○ ○ ○ Most Positive

Please explain. *

To what degree has the constraint matrix impacted your ideation or design solutions? *

1 2 3 4 5

No impact ○ ○ ○ ○ ○ Large impact

Please explain. *

Please rate your current attitude toward the constraint matrix. *

1 2 3 4 5

Most negative ○ ○ ○ ○ ○ Most positive

Please explain. *

Submit

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https://docs.google.com/spreadsheet/viewform?formkey=dEI3T3I3dWV4S2ICNk1qa19RSllabIE6MQ#gid=0 3/3

Survey 3: Control form

Please return by Dec. 13th

* Required

Your name: *

Please rate your current attitude about your design process: honestly assess the quality of your final design solution *

1 2 3 4 5

Very poor ○ ○ ○ ○ ○ Great

Please explain the reasons for why you rated your design as you did above. What do you feel could be improved? What was done well? *

Please rate your current attitude about the quality of your group's teamwork. *

1 2 3 4 5

Most negative ○ ○ ○ ○ ○ Most positive

Please explain. *

Rate the degree to which your group's final solution represents a consensus solution to the design problem: *

1 2 3 4 5

No consensus ○ ○ ○ ○ ○ Complete consensus

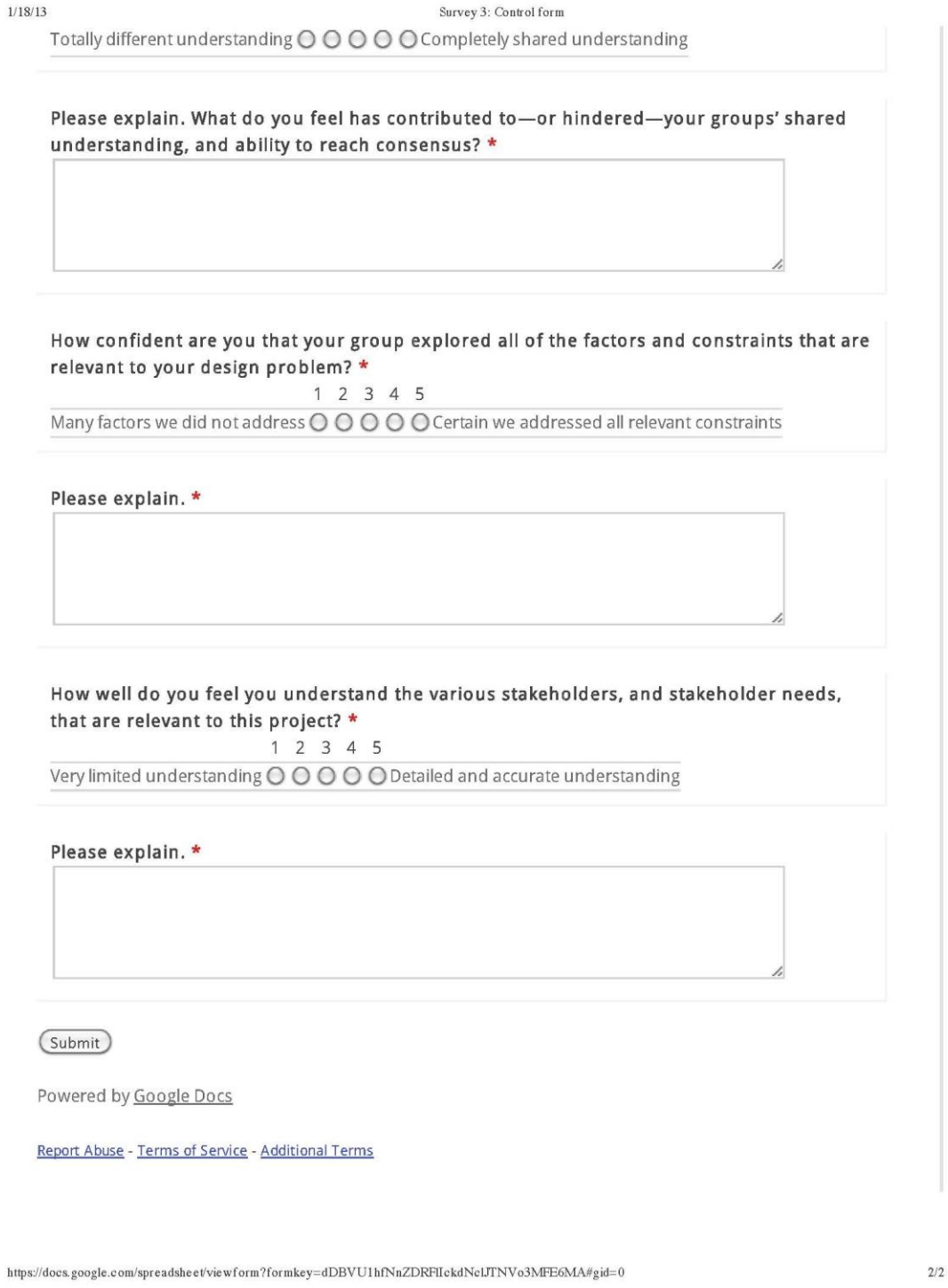
Please rate the degree to which your team shares an understanding of the design problem, its relevant factors, and the quality of your final solution. *

1 2 3 4 5

Continued

Figure B.5: Control student survey 3, given after the conclusion of the project.

Figure B.5 continued



1/18/13 Survey 3: Control form

Totally different understanding ○ ○ ○ ○ ○ Completely shared understanding

Please explain. What do you feel has contributed to—or hindered—your groups' shared understanding, and ability to reach consensus? *

How confident are you that your group explored all of the factors and constraints that are relevant to your design problem? *

1 2 3 4 5

Many factors we did not address ○ ○ ○ ○ ○ Certain we addressed all relevant constraints

Please explain. *

How well do you feel you understand the various stakeholders, and stakeholder needs, that are relevant to this project? *

1 2 3 4 5

Very limited understanding ○ ○ ○ ○ ○ Detailed and accurate understanding

Please explain. *

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https://docs.google.com/spreadsheet/viewform?formkey=dDBVU1hfNnZDRFlIckdNclJTNVo3MFE6MA#gid=0 2/2

Survey 3: Experimental form

Please return by Dec. 13th

* Required

Your name: *

Please rate your current attitude about your design process: honestly assess the quality of your final design solution *

1 2 3 4 5

Very poor ○ ○ ○ ○ ○ Great

Please explain the reasons for why you rated your design as you did above. What do you feel could be improved? What was done well? *

Please rate your current attitude about the quality of your group's teamwork. *

1 2 3 4 5

Most negative ○ ○ ○ ○ ○ Most positive

Please explain. *

Rate the degree to which your group's final solution represents a consensus solution to the design problem: *

1 2 3 4 5

No consensus ○ ○ ○ ○ ○ Complete consensus

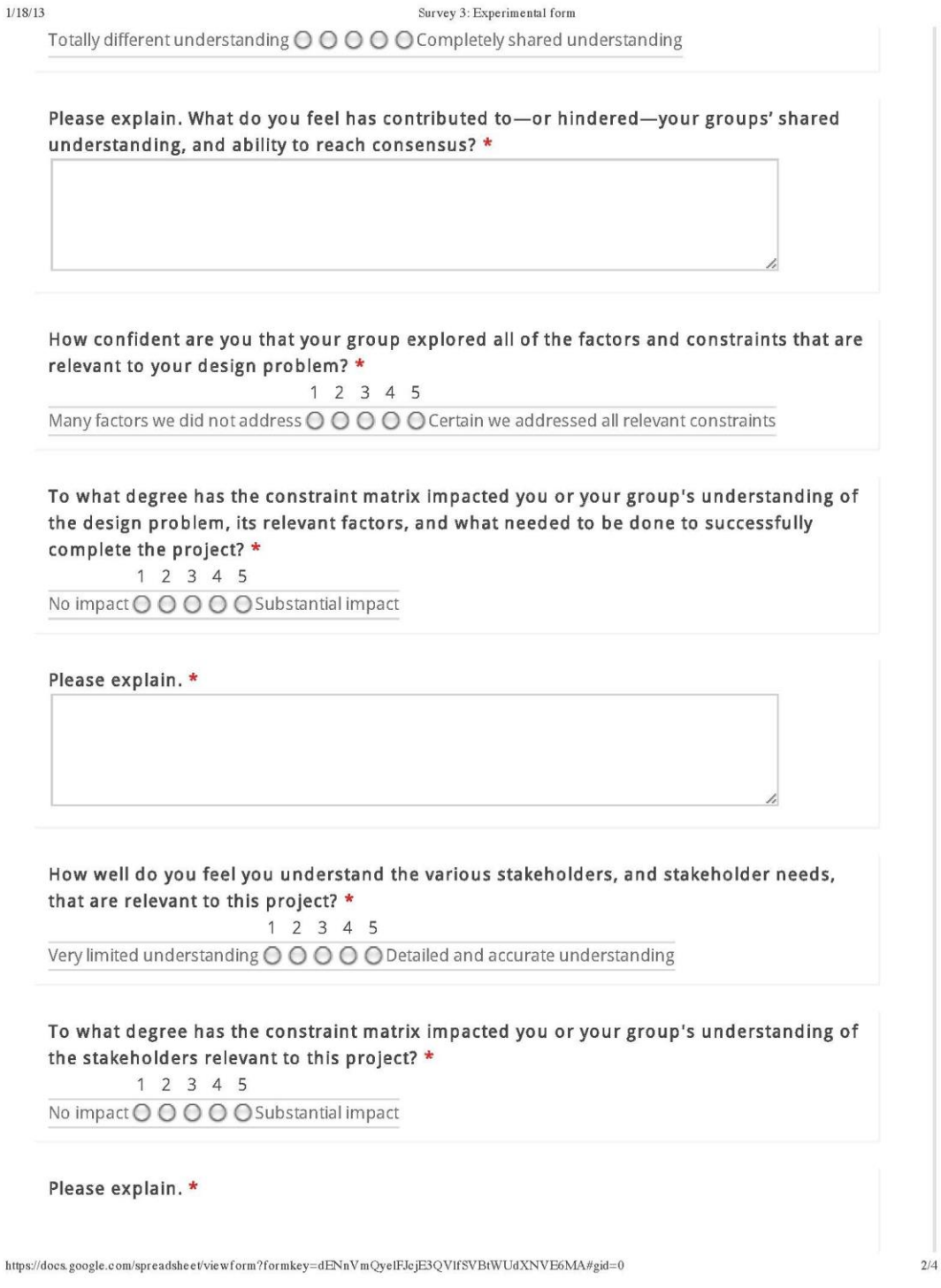
Please rate the degree to which your team shares an understanding of the design problem, its relevant factors, and the quality of your final solution. *

1 2 3 4 5

Continued

Figure B.6: Experimental student survey 3, given after the conclusion of the project.

Figure B.6 continued



1/18/13 Survey 3: Experimental form

Totally different understanding ○ ○ ○ ○ ○ Completely shared understanding

Please explain. What do you feel has contributed to—or hindered—your groups' shared understanding, and ability to reach consensus? *

How confident are you that your group explored all of the factors and constraints that are relevant to your design problem? *

1 2 3 4 5

Many factors we did not address ○ ○ ○ ○ ○ Certain we addressed all relevant constraints

To what degree has the constraint matrix impacted you or your group's understanding of the design problem, its relevant factors, and what needed to be done to successfully complete the project? *

1 2 3 4 5

No impact ○ ○ ○ ○ ○ Substantial impact

Please explain. *

How well do you feel you understand the various stakeholders, and stakeholder needs, that are relevant to this project? *

1 2 3 4 5

Very limited understanding ○ ○ ○ ○ ○ Detailed and accurate understanding

To what degree has the constraint matrix impacted you or your group's understanding of the stakeholders relevant to this project? *

1 2 3 4 5

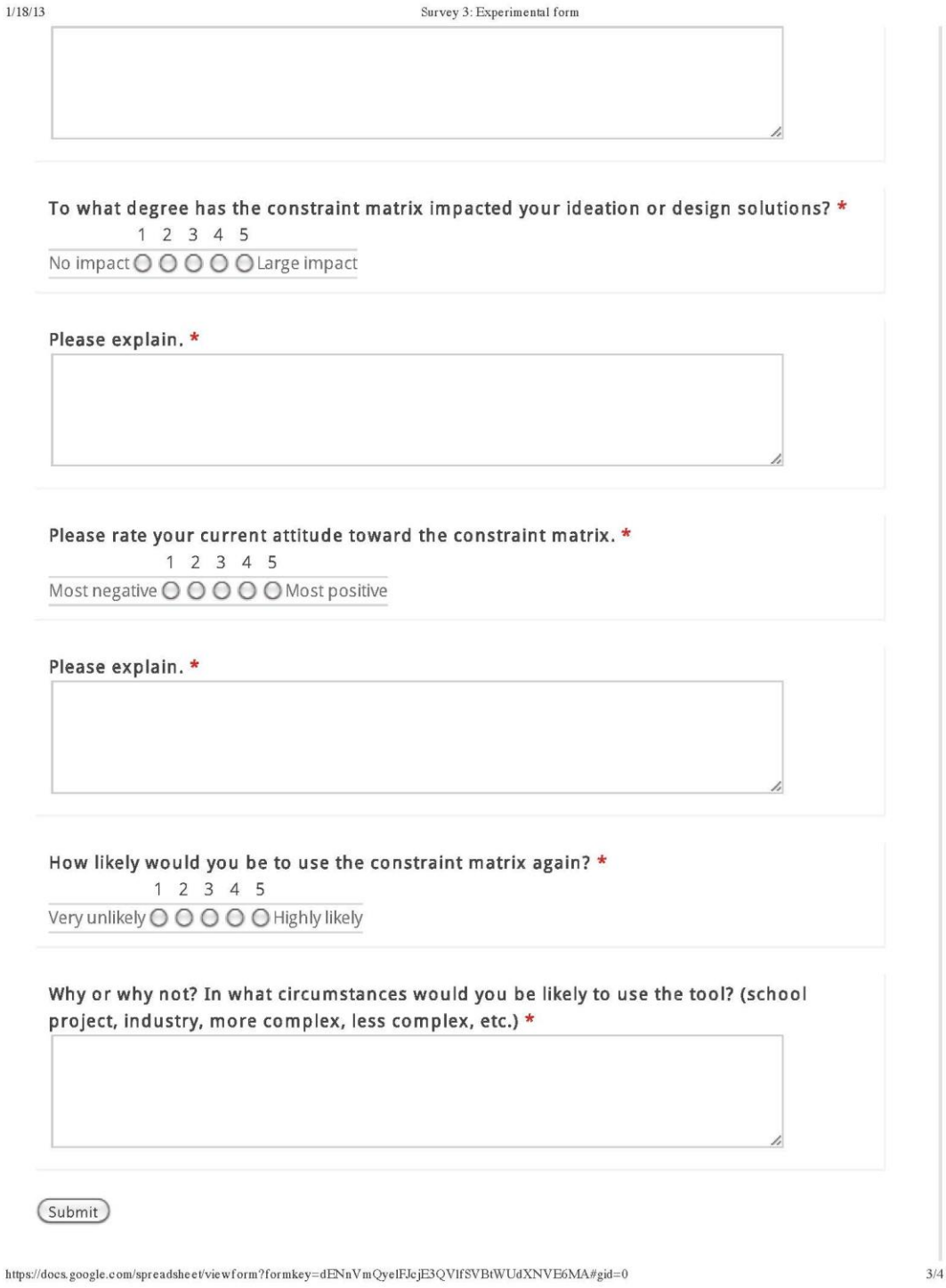
No impact ○ ○ ○ ○ ○ Substantial impact

Please explain. *

https://docs.google.com/spreadsheet/viewform?formkey=dENnVmQyelFJcjE3QVlfSVBtWUdXNVE6MA#gid=0 2/4

Continued

Figure B.6 continued


1/18/13 Survey 3: Experimental form

To what degree has the constraint matrix impacted your ideation or design solutions? *

1 2 3 4 5

No impact ○ ○ ○ ○ ○ Large impact

Please explain. *

Please rate your current attitude toward the constraint matrix. *

1 2 3 4 5

Most negative ○ ○ ○ ○ ○ Most positive

Please explain. *

How likely would you be to use the constraint matrix again? *

1 2 3 4 5

Very unlikely ○ ○ ○ ○ ○ Highly likely

Why or why not? In what circumstances would you be likely to use the tool? (school project, industry, more complex, less complex, etc.) *

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Appendix C: Student Responses

Control Population Data

	Survey 1		Survey 2				Survey 3					
Student ID	Attitude about design project.	Attitude about quality of teamwork.	Attitude about design project.	Attitude about quality of teamwork.	Shared understanding of the design problem.	Understanding of relevant stakeholders, and stakeholder needs.	Degree to which your group's final solution represents a consensus.	Shared understanding of the design problem.	Attitude about quality of teamwork.	Confidence that all of the relevant factors and constraints were explored	Understanding of relevant stakeholders, and stakeholder needs.	Attitude about design project and final solution.
1	3	4	3	3	2	4	3	2	1	3	5	3
2	5	5	5	5	5	3	4	4	5	5	3	5
3	3	4	4	4	4	3	3	2	3	4	5	3
4	5	4	5	5	5	5	4	4	5	3	4	5
5	5	4	4	4	5	3	4	4	4	3	4	3
6	4	4	3	3	3	3	4	2	4	2	2	4
7	4	3	4	4	5	5	3	3	2	3	3	3
8	4	4	2	2	4	3	3	3	2	4	5	4
9	3	5	4	4	4	5	4	4	4	3	3	4
10	4	4	5	4	5	5	5	4	4	4	5	4
11	4	5	5	5	5	5	4	4	5	5	5	5
12	4	5	5	5	4	4	3	3	4	4	4	4
13	4	5	4	4	5	4	5	4	5	3	5	4
14	4	4	3	4	4	4	3	3	4	4	4	5
15	3	4	3	4	4	4	3	2	3	4	5	4
16	3	2	3	2	4	4	2	2	1	3	3	2
17	3	2	3	2	4	3	3	2	4	4	3	4
18	4	4	3	4	3	3	3	3	4	3	4	3
19	4	5	4	4	4	4	4	3	4	4	5	4
20	4	5	4	3	4	2	4	4	4	5	4	4
21	4	3	1	1	2	4	3	1	3	2	2	4
22	3	4	4	4	4	3	3	4	2	4	4	4
23	3	4	3	4	4	5	2	4	3	4	4	3
24	4	5	4	4	4	4	4	5	4	3	4	3
25	3	3	4	4	5	4	3	3	2	2	4	3
26	4	5	4	5	5	4	5	4	5	5	5	5
27	3	4	4	4	4	4	4	3	4	3	4	4
28	4	4	4	3	4	4	3	4	3	3	4	4
29	3	4	4	4	3	5	4	4	5	4	3	2
30	3	3	3	4	4	5	4	4	3	4	5	5
31	4	3	4	4	4	3	3	4	4	4	5	5
32	3	5	4	5	4	3	4	5	4	4	3	5
33	4	5	5	5	5	5	3	4	4	3	4	4
34	3	4	5	4	3	4	4	4	4	3	4	3
35	5	5	2	3	4	3	3	4	3	3	4	4
36	4	5	4	4	4	4	3	3	3	4	4	3
37	4	5	5	5	5	5	5	5	5	4	4	5

Table C.1: Control population survey data.

Survey 1 Qualitative Responses (Control Population)

ID	Attitude about design project.	Attitude about quality of teamwork.
1		
2	I'm extremely thrilled to see what our group comes up with. I was skeptical at first about designing something meaningful when we were doing the first project (lighting) and ended up with something quite remarkable. This only means that what we will end up with for our main project will be as interesting if not more so.	We always meet, which is great. Everyone isn't meeting for the sake of physically attending our assigned meetings. Everyone in the group is more interested than just getting the letter grade they desire, which is great!
3	Currently my attitude if mostly neutral. I mainly just want to get it over with do to the large amount of work from other classes. I feel that if this was the only project I was doing it would be much better. But when you are trying to work around many things it comes off as just another road block.	The group seems to work well so far. At times do to lack of people showing up things seem to be diffiucult. But in general things are going well.
4		
5	Design is really interesting to me,	Not all my team mates seem equally motivated.
6	I'm excited to be designing, but am a little unsure about whether our concept will differ sufficiently from the current design to be interesting.	I think that my team is pretty good at working together, even though the communication is not perfect and we aren't always able to agree. Sometimes we talk past each other.
7	I feel like we have a project I am interested in working on and that we can really make something worthwhile out of it. We have all shown a tendency to approach problems differently, resulting in us having a lot of diverse ideas.	Though I understand we are all some form of engineers and have heavy courseloads outside of this class, I still feel like at least one of the group members is not making a real effort to meet up consistently and when we do meet, they often lack focus and do other things during the meeting. Aside from that, when we do meet and everyone is focused, we always seem to get good work done
8	We have a good idea of what we're redesigning, but unreliable contact with team members and the on-the-job contact has caused the team to develop very little momentum. We're behind and it may show in our work.	We tend to have very good ideas, but also tend to home in on a specific idea before other potential solutions are fully developed.
9		
10	I am always excited about coming up with new ideas. Currently feel like our current design project has real potential as a useful product in the real world.	Or team seems to work well together building on each others ideas.
11	I think that it is an interesting design that we are doing, but it is rather similar to what we did for the first project.	We work very well together and get things done early and do them well.
12	I feel like the scope of the project is too large. Even though I pretty much know what I am expected to complete, I still think I will be pretty overwhelmed when it comes time to make a prototype. In addition, our working prototype will likely have to be very large which will probably be very difficult to create.	So far we are working and interacting very well together. We have spent enough time on all our deliverables and so far they have turned out well.
13		
14	I'm really enjoying my current design project, mainly because I was given the option to choose what kind of product I was going to be designing.	I am content with the quality of my groups teamwork, however often differing views among our team has caused us to fall behind on the progression of our prototypes.
15	I liked the first project more than I like the one we are working on now. I liked how we were given the task of designing a light source but could do anything with it. I like that small amount of direction and then hands off the rest of the way. This second project is too open ended. I would have liked a small initial push like the first project. Maybe if we were assigned a user or at least an industry to keep it a little broad.	We work well as a team. We all want to succeed and we want to succeed together. Everyone has been good about investing time into the project and communicating well with each other. I have not had any problems with an individuals on the ream and look forward to the rest of the quarter with them.
16		
17	Although the problem we are designing for is valid and we might come up with a good solution, we didn't spend the time I think we should have spent to consider different user groups.	The two major issues are responsiveness and willingness to explore. Our team can also use more depth in the thought process.
18		

Continued

Table C.2: Qualitative response data for control survey 1.

Table C.2 continued

19	I'm positive we will come up with a positive design. We've just got the ball really rolling so I'm still a little leery, but I think it will turn out great in the end.	I feel like my team works really well together. I feel like we can all share our thoughts well.
20	It is a fun project but I feel that in many ways the constraints of the class setting, time, funds, ect. , make this project a little less than awesome	We work very well together
21	I think the design process is really important. I also feel that engineering applications will repeatedly "dip" into this information. However, without trying to be negative, semesters have people exhausted and interest in many aspects is dwindling.	Monday will be the: "tell tale" as we select a solution and begin the prototyping.
22		
23		
24	I am overall very happy with the project although I feel that I am a little behind on the schedule.	My team to this point has done a great job of really working hard on the project, and I hope to continue the trend.
25	We started off pretty motivated, but unfortunately that motivation has since gone away. Although I think once we get our ideas on paper we will be more excited!	We are not as enthusiastic as I would like to see.
26		
27	Since we have three projects going on at once and we're trying to figure out which one will be the best, it's a little nerve racking	We work very well together. Some times it's hard to get everyone together or on the same page, but in the end it all gets done.
28		
29	I choose a lower score because I am apprehensive about what our design is actually going to be. We have two Electrical Engineers in our group (myself included), and so far none of the things we have seen in person have any electronics or controls associated with them. I am still looking forward to getting started on building something, however.	We work together very well, but get off focus sometimes (as far as keeping in mind the user and less the novelty). Nevertheless we get along very well and haven't had any trouble getting things done.
30	We've been able to do pretty well on the past assignments so I'm feeling good about the project. It has been difficult and somewhat frustrating to continue to come up with new ideas especially since I wouldn't consider myself to be a very creative person.	We've done good work so far but we've also done a really poor job at communicating with each other so I think that has inhibited our potential somewhat.
31		
32	I like the premise of the project and have enjoyed the lab and lecture section of this class very much. However, I believe my group could have found a better project to be working on.	Our group works well together. We come up with some good ideas and our work load is shared evenly.
33	I really like beer and the brewing process, but the brewery proposed their own project, rather than allowing us to create one for them. Their project is more involved than I probably would have came up with for them (had they not chosen one for us).	Our group has a very good dynamic. We get along very well, we can communicate very well (thanks to iMessage) and we are committed to creating a worthwhile product.
34		
35	I feel excited about this design project. This is an opportunity to connect what we learn from engineering course with a real-world unsolved issue. Our group is here to make a change. Each of us including me are pretty involved in it.	It is great to work with such enthusiastic teammates. Each step of our teamwork is well organized. our communication is the key to solve any disputes and problems in our teamwork.
36	I like this design project a lot and I am really into it, but I take 18 credits in this semester, so other courses somehow attract my attention	Our teammates are passionate, we are very effiecient when we work together
37	Excited to shadow a surgeon and try to find a product that would make their lives easier.	great team, we work in harmony so far.

Survey 2 Qualitative Responses (Control Population)

ID	Attitude about design project.	Attitude about quality of teamwork.	Shared understanding of the design problem.	Understanding of relevant stakeholders, and stakeholder needs.
1	I feel we have a great problem to solve but not an efficient enough group to produce a great product in the time allotted.	Our group doesn't have any conflicts but we don't have solid way to generate ideas and a "team vigor" to really purse good design	Some of of our group gets bogged down in the specific task trying to be accomplished and do have awareness of the rest of the elements of the design and aren't constantly stepping back to objectivity make sure the design is doing what the user needs and not migrating away.	I think our group has a good understanding because the person we shadowed was very clear on issues they faced.
2	I was initially reluctant to go with rock climbing since I don't connect with the sport. I don't practice it, nor do I generally feel positive about it. However, in shadowing, researching and just seeing people rock climb, I've gained respect for the sport since I've found out that it requires a great deal of physical and mental power.	We have recently turned a corner by focusing more on the "ease of install" rather than innovating for general rock climbing purposes. This was an important step since we are stuck and wouldn't have been accomplished had our group not kept a positive attitude towards this project.	We continually meet to make sure everyone is on the same page. Furthermore, our end user, Andrew from the OAC, was more than helpful in meeting us multiple times. These continued meetings and updates keep us all on track.	To be honest, I don't quite understand what this question is asking.
3	The complexity of the task seems much larger than when we started.	everyone is working well. hard to come up with a design that meets everything though. Very complex task	We completely understand the complexity of the task. I feel this is also making it harder to do	I feel we are having some trouble it getting our heads around everything
4	I'm very excited to move forward with this project at this point.	We have been mired by a few setbacks, but everyone is doing the best that they can inspite of these issues	At this point, this does not apply due to the fact that we have been unable to shadow our subjects yet	At this point, this does not apply due to the fact that we have been unable to shadow our subjects yet
5	I don't like the area we chose to work on.	The team does not seem very enthusiastic in doing the work.	We have all discussed the problem and I think everyone has a good understanding of the problem and its relevant factors.	We have not really interacted much with the shareholders.
6	I am still excited about the project, but I'm afraid that other members of my group are not.	It seems to me that the desire for us to excel in this project is relatively low, on the whole. We work together pretty well when we are together, but we aren't getting enough done during those times.	One thing that has hindered our group's understanding is having so many different feasible options. In addition, in our most recent meeting, we did not really address what we set out to, namely, defining what we are trying to do and how best to communicate that.	I feel we have a pretty good grasp of the user and his needs, since we have met with him on more than one occasion. On the other hand, I don't have a good grasp of the needs of the people who buy the equipment that the user works with. Not to mention, I don't know what kind of corporation would be producing what we design, so it's hard to define the corporate, marketing, and manufacturing stakeholders.
7	I am really enjoying the project. It is one of most interesting things I have school-wise, only problem I have currently is finding the time I would like to spend on it between all the other end-of-semester assignments I have.	We have been getting much better at getting together and progressing our design forward (aside from the last week). When we have gotten to meet, we have thought of many additional ideas that have helped take us in interesting new directions	I think we have a very good idea of the problem as a whole. We have defined the many different things that need to be balanced and implemented properly in order for our design to potentially successful. I would say the single most useful thing we have done so far in the process was starting work on our communication prototype by looking at a normal product similar to one of the configurations of our design. It allowed to to look at places where modifications or complete redesign could be useful.	I feel we understand pretty well the various stakeholders and what they would want. It is in fact this understanding that is making it pretty difficult to try and balance all the things that need to be done well to have a good project.

Continued

Table C.3: Qualitative response data for control survey 2.

Table C.3 continued

8	The design problem is so simplistic that it feels as though there is no room for ingenuity. Frankly, it's boring.	There is very little work done as a team. The team has very different goals, and as such, quality and involvement of work differs greatly between members.	The simplicity of the design problem lends to a very good understanding of the flaws in the current design and the requirements of a solution. Some of the finer details about the situations of use are less clear.	While the basic needs of the stakeholder are relatively straightforward (in this case, basically that of a handyman), one particular team member's overwhelming familiarity with the profession being designed for causes the professional contact to interact with the team in a different manner than he would otherwise.
9	If we can get a good amount of the prototype finished in the next couple of weeks we'll b in good shape.	We have been moving toward a common design, while exploring many options.	The project is very open-ended, so it's hard to decide how large or small, simple or complicated the product needs to be.	Talking to the potential user and walking through his actions on the job helped us understand the underlying problems in current products.
10	Interesting and fun.	Work well together and all contribute to the design	Everyone is enthusiastic about the design and sees potential with it.	Shadowing our user has been the most beneficial for understanding his needs
11	Better than last week. Now we have direction to go in, so we can start working on our prototype. For me this is a big step forward since my favorite part of any project is when I get to use my hands to build something.	Pretty good, we have good communication early, everybody is chipping in, and we have a few good ideas to pursue.	We have a lot of ideas, and that is one problem, We haven't settled down on anything yet. However, that also grants us flexibility. If our first idea doesn't work, we have something to fall back on.	We have an avid cyclist in our group, and our instructor is also a cyclist. Therefore, two people that are very involved in our project are our stakeholders.
12	I've been having a good time thinking of solutions to the problem and brainstorming ideas. It is very helpful that everyone in our group actively looks to work on the project and we are taking a "all-in" attitude towards it. Discussing ideas and the pros and cons of those ideas is definitely one of my favorite parts of this project so far. We are having a little trouble thinking of ways to implement ideas onto our prototype because the prototype is scaled quite a bit down into a model.	I feel like we had a great communication prototype and we were able to get some good feedback during class. We all spent about equal time together to create the prototype and made something that we felt was of good quality.	The product we are designing has little impact on any of our life experiences, since it deals with dairy farming. We do have good resources in knowing someone who has worked on one and he is able to give us good feedback.	Similar to the last question, we have never actually used the product so it is not likely that we know all the problems the stakeholder goes through. We are able to talk to them as much as possible and we are aware of all the problems that have been communicated. This set of problems could still be different than actual conditions.
13	We are working hard and the more time we spend on this the better the project will be. But if we dont put much effort into it then the design will not be as successful. Im hoping we put in the time to make this project great.	Everyone was there and working hard on the project. We just need more communication to get to the level 5.	Our group works best when we are all together spitting ideas out. If one or two people or missing then our ideas are really hindered but when the entire team is together working in person the ideas flow and great things are created.	Its hard to fully understand the project needs of a dairy farmer because we don't normally encounter these issues.
14	I am currently pleased with my design project, however am not too fond of the current direction our group is heading and the dropping of several of my ideas.	I am currently pleased with the quality of my groups teamwork, however I feel communication among our team needs improvement.	I team is very much on track when it comes to understanding the dsign problem and what needs to be done to successfully complete this project, however I feel a group conclusion needs to be made to determine what direction we are going to head from here on out.	I feel I have an understanding of the stakeholders and their needs in relevance to this project
15	Once we get an idea that our user is on board with and have a working prototype, I will feel more comfortable. At that point we will have something to show for out work. I know that we have done a lot of work up to this point, but I feel like we do not have a lot to show for it.	I think our group is working very well together. We hit a roadblock and realized the direction we were going in was not promising. We have used the information we learned to generate a plan for a new direction of our project. Everyone has	I think at first we had tunnel vision on a specific problem. The problem was rock climbing holds spinning. Once we found a decent idea to solve the problem we were convinced that was the only way to solve the problem. We just recently	We understand that our design will affect everyone who climbs on the rock wall. It will affect the rock wall setter the most since it will hopefully make their job easier. It will also affect the rock climber because if the setters job is easier there

Continued

Table C.3 continued

		stayed positive and open minded throughout this process.	realized we need to take a step back and not just analyze why this 1 design wouldn't work.	will be more routes with more variety of holds, moves, and skill levels.
16	i really just hope it gets done, im tired of having to fight with schedules this quarter and am ready for it to be over. the whole thing has just been more trouble than its worth. its just a little frustrating having to smash schedules together like this to make some goofy product that will never be used anyway.	i just feel out of the loop, when i make progress on something they never want to meet up to discuss it, and i always get stuck having to work around their schedules.	one of the group members used this tool we are designing for a previous job, so he is well aware of what some good designs would be. the other group member is just clueless and had no concept of how to solve real world problems. complete facepalm with most of his comments, just worthless.	not really at all because there is nobody that had anything invested in our project, were just doing it just to do it.
17	We still have a lot of options on the table. Some are more practical than others, while some satisfy more constrains. At this point, we should be having a clearer idea of our direction.	Members seem to not be familiar with some due dates. The team don't really care whether we are falling behind. However, they show some support when I want to propose some ideas.	Sometimes, we are reasonably critical of one-another's ideas. This criticism can help share our opinions and concerns.	I think I can identify several stakeholders such as direct and indirect users, material suppliers, and marketing people. However, I don't know how exactly these stakeholders are affected. When we settle on a certain concept, further exploration should yield a better picture.
18	I still feel optimistic about the success of our project, but at this point I might be concerned that minimal progress since last week is the reason for a step down from last week's response	Nothing has changed at this point. Our shadowing was delayed by our contact/subject of study.	Time constraints have, and I expect will continue to be, the number one challenge within the group.	I would say that I have done a decent amount of research, but I think I need a better understanding of the regulations regarding usage and compliance to better explain.
19	I think it's developing like we'd like to to. There are still things we need to think through but I like we're definitely moving down the right path.	I feel like we're in a good spot right now still. We've gone and talked with our user multiple times now and the more we do that, the more it helps.	I feel like we all have a good understanding of the different problems. I think what has contributed to the lack of totally understand might just be the language barrier and not understanding the whole process of our user. We've had to go back to him multiple times to ask questions about what we don't know but other than that I think we have a good understanding of everything.	There are still things that we don't fully understand about our user so that I think has hindered our progress a little but we also just ask the question and then we are back to work.
20	with a lot of work... this could turn out awesome	It is crazy how some people just don't understand simple mechanical concepts and principles. We definitely need better brain storming capabilities in our group.	We can all understand the scope of our project pretty well. This helps us get to a common goal.	Its not really easy to see where this project has the capability of going. It could turn into something amazing, it could wind up being a flop. It is therefore hard to know about the stakeholders.
21	This project has been excessive and rushed. I enjoy the content but I do not enjoy this project.	My ideas were blown off. I was the only one required to gather pictures. Apparently these weren't good enough so people would like it if I somehow found time to travel thirty minutes out of my way, bother the contact...again... and get ONE more picture.	Seems like everyone has different ideas of what the problem is. Hopefully we converge soon.	An additional contact has been very informative of potential use.
22	I think this idea will be more interesting than our original idea.	We work together well and influence each others ideas in a positive way.	We have been slightly hindered by taking the project in a different direction a few weeks in.	We haven't been able to job shadow yet.
23	Our project is ok, but I would have rather stuck with a user and problem that was more physically based than what ours is.	I think that all of our group members did a pretty good job of coming up with their 15 product design ideas.	I believe that we all understand it for the most part, we are just having trouble finding the physical component in our design idea.	I understand them very well, especially after shadowing our specific user.

Continued

Table C.3 continued

24	I am for the most part enjoying the project, it is fun to get an opportunity to design a product based on interaction and not simply engineering analysis.	I feel that we have done a good job with our work so far. However we have chosen a difficult task to undertake because so many of the components that comprise an ambulance have been refined in the past.	I feel that each member of our team is very aware of the various problems and understanding however we still disagree on the small details of how to solve the problem.	I feel that we understand the user side of things very much. However we have not yet spent time looking into the market side of the device.
25	We feel we have a good idea and we're motivated to make it better.	We have really kicked it into gear after coming up with a good idea.	We all are on the same page.	We have all visited the stakeholder, which has really helped.
26	Although I think we will be able to make a great design that will be able to address the problem effectively, I am sad that we will not have too large of market. We will be limited specifically to microbreweries due to the size of our design. It would be too small for a plant, and too large for a home operation.	Over the past weeks I have had a great time bonding with my design team. We have had fun building the prototypes, and visiting the brewery.	I feel that everyone on our team is on the same page. We understand the problem as well as the constraints. Although we all have separate ideas, we have had no difficulties in incorporating everyone's different strategies into our designs.	By going out and interviewing the owner of the brewery and some of the operators, it has become clear who exactly our stakeholders are, and where we would have a market for our product. Without talking directly to who has the issue, we would've never identified the operator as a key constraint as well as a stakeholder.
27	Even though we're a little behind, we are still on track and we have some very good ideas coming up.	Even though we had a lot of barriers thrown at us, we kept working toward the final goal, and whenever someone had a idea "seed", we could build upon it together very well.	I think that since we all know the final goal of our product, we could come up with many different ways of getting to that final goal.	Since we are very close to our stakeholders and some of us are stakeholders, it has made it easier to come up with ideas since we can bounce ideas off of them and we had immediate feedback.
28	I would like to see us have made a little more progress at this point in the game.	I think we need to move forward a little more quickly with our designs.	I think everyone understands the problems, but we are struggling to come to a consensus on the best way to approach and solve the problem.	I think the shadowing helped alot with my understanding and also reading available literature about our user group online.
29	Our progress has been good so far, but I am apprehensive as to how we are actually going to present our final idea. In real life, it would be quite a large structure, made of mostly metal tubing, which isn't very feasible to create for the class (and more expensive than we would be willing to spend on it). Thankfully, we all get a long well and have no problem working together.	The teamwork is good. However, the item itself has potential for very little alterations or methods, making it hard to be creative with our solutions. I do wish that our proposed idea was a bit more complex, so that more out-of-the box solutions were applicable.	I feel a lot of the group methodology is focus souly around making it easy on the user (in the physical sense), as opposed to how well it will actually work at it's task. Also, we really put all of our chips into one basket, relying on the one trip to give us a good idea. Unfortunately, the dairy farm operator didn't have a ton of problems that were very underdeveloped, or things that would be applicable across a range of markets (other than farming/agricultural)	The purpose of the device, and it's need, is pretty straightforward, and we know exactly what it needs to do. This is good in the sense it gives us a good focus as to what we need to design, but leaves little room for variation, or outside application.
30	We're a little behind so I'm a bit discouraged there but I also know we've done good work in the past and we've made decent progress this week to work on catching up.	We're doing good work but still struggling with good communication which is hindering us a little.	We have all ridden bikes so in that sense we all understand the problem through that to a degree. But I also have a lot more experience with bikes (especially riding at night) that does the rest of my team so they don't have that understanding as much as I do.	Being a cyclist, I am pretty much who we are designing for so I feel like I understand the needs of the project very well.
31	Looking forward to building a prototype.	We work pretty well as a team.	We are pretty much on the same page on many ideas and thoughts on how to proceed.	We have understood our target user's idea of the product fairly well.
32	I think we have some good ideas and have a solid way we can improve upon it. However, there are still a few sticking points we are stuck on finalizing the design.	Our group has done a great job coordinating around each others schedules so that we can each contribute to all parts of our prototyping process.	All of our group member seem to all have a good understanding about what is going on. However, we do not all seem to bring the same amount of ideas to the table; which leads me to believe some understand it better.	Although we spent a good 3 hours shadowing our stakeholder there was just too much to learn in one visit. Also we did not get to see the whole process of the use of this product.

Continued

Table C.3 continued

33	I think it is pretty viable and I enjoy working on it. I am excited to see where it goes from here.	Everyone gets along great and is willing to participate	iMessage has helped with the communication, we all have iphones and it makes messaging very simple.	We have talked directly to the owner and he knows exactly what kind of product he is looking for. When we have had any questions we simply meet with him and work it out.
34	I think as we have come along in the past few weeks and developed and changed a lot of ideas about our design we seem to be heading in a very interesting phase of the design cycle. All the brain storming and meetings have helped move in a direction that we had never thought of in the first place and the project seems to have a really interesting side to it with the merging of ideas and 2 different products that we started of with.	The group seems to function pretty well coming up with ideas before meetings so that there is something to work with and discuss and move along with the project in the right direction. If any one is missing the group members make sure to inform the missing person about what happened and make sure they have all the information discussed as well as what is due the next time the group is meeting so that everyone is on the same page with the project.	There seems to still be a little confusion between completely software based solutions as compared to design and ergonomic solutions.	The shadowing process helped get a feel of the stake holders work environment moreover being able to talk to the person about what it is they want and at the same time see the constraints of their work environment has given us some insight into what the problems and possible solutions could be.
35	we encountered some problems. Right now we have to switch focus from path identification. Not sure about what we will get.	We started at a very good direction. A lot of different improvement could be done for rock climbing. But our ideas are proved less feasible. We have to remove from our current focus. This will take more time than we planned.	We definitely have shared understanding. However, a lack of comprehensive understanding of rock climbing has slowed down project process.	I used to think from a rock climber way to correct some problems happening to myself. But these problems are not common for everybody. Furthermore, rock climbing wall is not like a random wall we can customize. So are the holds.
36	I am very positive to the project, and I think our product would be very useful in the end, and this make me become more positive	It is very positive, we are approaching our goal now, every thing works fine	we have very good understanding	It is very important, continuous communication can contribute a lot to the understanding
37	I'm very excited and optimistic about finishing the project and actually see if your design would help.	We all work great together	we all understand the problem and are working to find a solution	Shadowing was an essential step for a better understanding of the project. without shadowing it would have been hard for us to understand whats going on especially it's not related to our field.

Survey 3 Qualitative Responses (Control Population)

ID	Degree to which your group's final solution represents a consensus.	Attitude about quality of teamwork.	Confidence that all of the relevant factors and constraints were explored	Understanding of relevant stakeholders, and stakeholder needs.	Attitude about design project and final solution.
1	Not enough time together coming up with ideas as a group. Most the ideas we came up with separately and just thew together into the design.	We didn't have any conflicts but we didn't really work as a group, everyone just kinda did their own thing and we put to together without any real vetting of the ideas.	The problem we choose was to broad in retrospect, and thus it was hard to constrain the problem, which in turn made the design focus hard to figure out.	I think we understood the problem, it was just to broad to develop a specific product for the purpose of this class.	Our design have an good overall idea but lacked those details that makes a design great.
2	Prior to making any changes or applying any of our ideas to our prototype, we made sure everyone knew what will be done. We always proposed ideas on paper before going ahead and applying them onto our prototype.	Our group really worked together on every aspect of the project. We all collaborated on the Powerpoint slides, Executive Summary and on the prototype.	We made sure, before making the prototype, that we met all the requirements and needs of our user.	To be completely honest, I don't quite understand what is being asked here. Sorry!	I feel like our group has done a great job reflecting on what our user thinks primarily. We feel like our user knows what's best and what he needs. Our continuous discussions and meetings with him made for a successful outcome.
3	I feel that the conveying of ideas was hard for this project due to the complexity of it and the use of CAD before beginning the prototype would have been helpful.	We got the work done I would rate it more at around a 3.5. I wish we were able to get stuff done sooner. At times if felt like things were done to last minute for my liking.	I feel we have address many of them but due to the complexity of it some have been overlook in order for us to be able to reach a final design.	I feel from talking to people we were able to accurately understand their issues. However it was no easy to include everything the wished for	The design could be improved to be able to accommodate more wheel chairs. Also not have a full scale and working model that could be through tested to determines where it falls short.
4	I think we did a great job of recognizing various problems that we observed, and chose an excellent problem to tackle in the context of this project.	I think our group had great teamwork dynamics, everyone has alot of work to do however, when someone had prior commitments and or was sick. etc. Everyone else picked up the slack to accomplish the task at hand.	I think that what we produced was a great start, however, there are also some other features that would need to be on the final product for this device.	There is at least one very common surgery that this device will be useful for, however, there are other surgeries that this device may be useful for that we have not yet explored.	I think we identified a problem that the surgeons didn't even realize was a problem. With out solution it free's up their non-dominant hand to use a more useful tool than a mirror for pushing flesh out of the way. This also allows them to continually see what they are working on during the procedure.
5	Everyone was given a chance to speak and make them self heard. If any idea was rejected, it was done respectfully.	everyone put in effort equal effort.	I think we didn't consider all of the constraints.	I believe we did understand the needs of most of the stakeholders.	I just don't think our design was very practical and makes much sense. Initially the group was very enthusiastic but as the semester passed that changed. I think our design would not have any real applications.
6	I think the fact that we were addressing several problems, and had considered addressing several others, kept us from having a totally shared understanding. Nonetheless, I think the primary focus was clear to all of us.	We were able to make design decisions fairly quickly and without excessive conflict. When we met outside of class, usually we were all present. When working on the prototype, everyone did their fair share.	I think that we addressed most of the factors, but in order to be more confident, I would have wanted more face time with more people in the population that would benefit from our design.	I think that I have a fairly good idea of who the stakeholders are, but in order to be confident about having an accurate understanding of their needs, I would have needed to talk to these stakeholders, which our team did not do.	I think our design adequately addressed the problem we identified, but because the problem wasn't so compelling (in my opinion) and the solution was simple, I don't think I can say our final design solution was great.

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Table C.4: Qualitative response data for control survey 3.

Table C.4 continued

7	The only thing that really hindered it was the lack of time spent working together as a group	Our teamwork never really did catch its stride through the class. Eventually, it ended up being just a single individual that did the vast majority of the actual work, though everyone did had decent input during design meetings	We certainly got many of the main ones, but every time we got to a prototype design stage, we often discovered new things that we hadn't considered and needed to revise. This again was the case when we put together our final prototype	We feel like we had a pretty good understanding of this aspect, as we all had at least some personal experience through which we could relate as well as our communication with the target user	While I liked our idea in the final design, it just wasn't polished enough. Even once we had settled on a final design, there were several issues I still had.
8	The team has a very good understanding of the problem, and it was very capably solved. The solution, however, raises other potential problems which I felt needed to be addressed.	The purpose of the generation of the 15 concepts was, in part, to develop many solutions to one problem and incorporate bits and pieces of those concepts into one final design. The design chosen and developed by the team, however, didn't benefit from the other 44 concepts designed by the team.	Implementation of a new product to replace a simple and ubiquitous design would be incredibly tricky, and I don't think my team thought enough about the transitional period.	Understanding the stakeholders was incredibly simple. One one hand, users in the field desired ease of use. On the other hand, the design of the device is such that it is only easy to use by those who need to use it, know how to use it, and have the means to do so.	The design my team landed on addressed all the problems we set out to solve, and did it in a somewhat novel way. The communication and workshopping of the idea could have been vastly improved, however. All in all, we ended up with a good 1.0 product, that would benefit from further consideration.
9	We understood the main problem with current products thanks to our interview with the user.	We worked together well to make our prototype turn out well.	If we had talked to other similar users we may have found more design factors to address.	We talked with the main user about his needs, but we didn't communicate with secondary users or manufacturers.	I think our final product turned out really well. We got some good feedback from our user and from other students.
10	It is difficult to say why we did. We worked good as a team, and unlike other groups none of us had big enough egos to conflict with each other. Also meeting and shadowing our user as a group really helped us converge on the same design solution	Everyone was positive and all agreed on the final design. With all group projects you need to have some leader to delegate which we did pretty well. We also understood each of our strengths and weakness and tried to use different strengths to accomplish the final design and report/presentation.	We really got to understand the constraints when meeting our user a second time with our 3 communication. Prototypes. Discussing this with our target user was very beneficial for understanding his needs	Like I said above, showing the communication prototype to our user was critical.	The design process had a huge impact on our final design. We could not have gotten to the final design without going thru the steps. The communication prototypes were key in our case to getting to the best design. I think by making multiple communication prototypes was key to our success.
11	Since we got together and met up quite frequently about this project, we made sure that we were all on the same page the whole time. Through our communication we were able to reach a consensus.	We all contributed greatly to this project and brought some of our own experience and expertise to the table.	Our multiple meetings with the mechanic allowed us to really see all of the factors that went into our design. I think the key step was when we brought our three cardboard prototypes to him for feedback. We got a lot of detailed thoughts from the user which helped shape our final product.	Again by speaking with the mechanic throughout the process we were able to keep to what he needed to be done.	I think that it was very well made and constructed. Every part of it was thought about extensively including how to make every little bend and cut out of aluminum sheeting. We planned it out very well so it was very easy to make when the time came. The only downside was the magnets losing their power.
12	As always, we were working on a problem that none of us had personal experience with. We could potentially be way off in our solution. Since no one had that experience, making design decisions came down to pure persuasion skills. No	We all worked very hard on creating the final prototype and I feel like no one slacked off. We all pretty much did equal amounts of work and since we did that, making the prototype never seemed like much of a chore.	Same as last question-- none of us had personal experience. I know it is likely we missed a couple constraints that were never brought up to begin with, but I feel like what we created was an excellent rough draft prototype that	We would have to bring the prototype back to the dairy farmer and see what he thought of it. To the best of our knowledge, our prototype would definitely fix a problem seen in this field--- efficiency of laying hay for the	I felt all our ideas where accurately depicted into our prototype. It was essentially completely functional, granted it was a scaled down size hay unroller. It would allow us to bring it to the customer and go over all the features and

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Table C.4 continued

	one really knew what would be a good idea, but whoever was able to sell their ideas best usually got their ideas implemented.		could be brought out in front of dairy farmers for additional comment and criticism.	cows. Whether there were any other needs that were at a higher priority is an unknown to us, but we feel whether or not there are, we surely did something that was a net positive for the farmer.	get more feedback if we decided to take that route.
13	We were all able to attend the farm and see the problem first hand so we all knew the background. We were then able to reference the same concepts to get the job done.	Our team worked great together. I gained two new friends from this group and we were able to work well together. Even though the 4th member I dont consider a friend I still feel like we were able to work well together and get the job done. He just has a different personality then I do.	Id say we were in the middle here because of the material strengths of are product are important. I would have liked to come up with a more integrated solution but that would have gone against almsot everything we learned in class so we went very simple.	The need is to get the food(hay) to the field with as little effort in the least amount of time to make life easier for the diary farmer.	I really like our design and think it could be very useful in real life application. I am worried about the strength of materials and the positioning of the wheels. many iterations and tests would be necessary to find the best for both.
14	Strong personalities on the design of our product has slowed and possibly hindered progress at times, however I feel we all came into agreement on the final design.	I am happy with our groups current work and communication between group members.	I feel if given a little more time and the funds our group could have effectively countered several constraints still relevant to our design, however as a whole I feel we explored all that we could.	I feel I have a much better understanding now regarding stakeholder needs when developing and furthering a design.	I felt our group effectively evolved our design since the last survey, and am very content with the current status of our design. I feel we effectively worked together to bring together many of our ideas into a single design.
15	Language barrier - It was difficult at times to get the international students in out group to understand the concepts we were discussing throughout the project. Engineering Background - The group members who were ISE and ECE had trouble understanding technical mechanical engineering concepts that we knew from class. Lack of Communication - There were a couple instances where we all thought we were on the same page but were not because we did not fully communicate with each other.	Once we get everyone in 1 place, we work very well as a team. We are good at dividing up tasks based on our strengths are really want what is best for the group. Getting everyone to find a time to meet or to come to meetings on time has been a problem. Certain team members value the class more than others which let to slightly uneven work loads on the prototype or presentation.	We did not fully explore the usability of the device with regards to the size of the body and of the button. We got caught up on making a good presentation and making a prototype of the ideas we did have that we could not fully explore usability from an ergonomic standpoint.	I believe I understood the needs of all stakeholders very well. We met with our user enough to truly understand what he wanted and how this product would affect his job. We also kept him updated along the way with new ideas that we had to make sure they would meet his needs.	I think that if we had more time (maybe only 1 more week) to work on our design it would be a 5 out of 5. If we had the foresight to pursue the "path redirection" issue as opposed to the "hold spinning" or "hold labeling" we could have had more time to really develop our ideas. Changing directions happens frequently in the design process so having to do it was a good experience.
16	the fact that one member cant build things and has no concept of how mechanical things work, and the other member has is head in the clouds and cannot come up with practical solutions to anything. and im stuck in the middle with real solutions that never get built because they make too much sense.	well our one member said he wanted to "play to his strengths" so he did the paper and presentation by himself, because an engineer who cant build things is not that uncommon in OSU's ME program... and the other two of us spent crazy hours in the machine shop building the prototype that was going to be	the thing we made is probably not really that easy to produce on a large scale, and realistically people are not going to change the way things are currently.	i dont think there are any stakeholders for our project.	it was just kind of overkill, its really not practical and there is already a patent for the type of device we produced.

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Table C.4 continued

		"easy" to whip up. too bad it was like 30 hours of machining that went into it.			
17	I think we needed to get back to more users and use more passive ways to get the information. We didn't have as much information as we needed, which led to some confusion about what is more important.	Everyone contributed to the project. And the solution we reached would appeal to customers. However, our design would have evolved much further if we had the prototype earlier.	One of the constraints we started with was not focused on as it compromised convenience.	We mostly focused on our final user. We didn't really consider "intermediate" users in marketing and production, since we spent the time mostly developing the concept and did not finalize our choice of the material and production processes for the final product.	Our design, although solved the problems, introduced what might be points of inconvenience. I think we should have given it to our user for a sufficiently long test.
18	We all did the shadowing and design process methodically together. So I think we all understand the scope and agree that we did the best for the time we had.	Everyone worked well together. Sure there was some differences in opinion, but it was mostly about going a certain direction because it was easier. We worked well together.	Unfortunately, all but one of us was in 5 graduate classes. I would have liked to explore more of the constraints, but we would not have been able to put more time in. As it stands, I spent more time on this project than any other class.	I think I've stated above the major challenges to a deeper dive, but I definitely think we have a really good understanding. As with anything, it could be better.	Truthfully, I think too often we took the approach of doing what was easier or what we could present or finish in time instead of really digging in deep and actually letting the design process downselect. For what we did choose, I think we did a great job.
19	I feel like my group well represented our problem and solution to the class. I think our pictures definitely helped. I think our only problem might have been the lanuage barrier.	I feel like my team worked very well together. We all were willing to sacrifice time and do the work needed to complete the assignment	I think we could have done a little bit more with the different constraints but overall we hit most of them.	I think we understood very well the various need of our stakeholder	I feel like we could've done a little bit more with our product had a had even one more week. Overall thought I think it turned out well.
20	we all spent a lot of time together talking through the design problem so we all understand it very well.	Good but some in our group were rather ignorant about fabrication techniques. This led to some interesting ideas being passed around about what our design should look like.	We spent a lot of time in the field and making prototypes. We discovered a lot of new things and addressed them in our final prototype.	Hard to say what those would entail at this point in the project. We only had a prototype done.	It was an awesome solution but our magnets failed to be as strong as we wanted due to the machining process so it didn't work too well
21	I feel as though there were misunderstandings regarding the project due to personal perceptions of the problem.	Everything we needed to accomplish got done. Not necessarily in short order.	I feel as though there could always be alternative measures.	As far as the immediate user's needs, I feel that most issues were addressed. Beyond the immediate user I am not sure what else should be considered.	As far as the prototype is concerned, I feel it communicated the features we thought were most critical. I felt as though it was really effective.
22	We did understand the problem well and we all agreed on the final solution.	When we were together we worked well but half of the people wouldn't show up to the meetings most of the time. There was also a lot of arguing about what project to do early on which is why we were behind schedule.	There were a couple features that we thought of late in the design process, after we showed our user, and were unable to implement them into the device.	We asked the user about the product before we began the design and after we came up with a communications device. We really listened to what she had to say in both cases.	We rushed to finish in time and could have added additioinal features that would have really made the product more marketable.
23	I think that every member of my team had a thorough understanding of the problem, factors, and our final solution. I believe this is why we were able to come up with as many solutions and features as we did.	I believe that my team worked together pretty well. The only impediment was that group members were often not as enthused about the class or project as they could have been, including myself.	I believe we explored almost every facet, but there is always going to be something that you overlooked.	I believe that I have a thorough, albeit imperfect understanding of the user and stakeholders. The user my group selected was someone we come in contact with in everyday life and our interview user	I thought that my group did well communicating the final prototype considering much of the solution was softwear based. However, I feel as though the idea could have been more unique and

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Table C.4 continued

				was very insightful and helpful.	innovative, I just don't know how.
24	I believe that our many group meetings and discussions have lead to a complete understanding of all the different components.	We worked well as a team it seemed as though everyone contributed and things went smoothly.	I don't believe that it is ever possible to completely explore all possibilities, there is always room for improvement.	I still feel that our team understands the user but not the market for our product.	I feel that our design was well thought through and does actually solve some major issues. However the changes seem very bland because they are fairly straight forward.
25	We have spent time together working on the project, so everyone is on the same page.	We worked well as a team, but only when we had motivation, which was rare.	We could have spent a lot more time exploring. We mainly got an idea and went with it in order to simply finish the project.	We met numerous times with the stakeholder, which was a great help.	We sort of got stuck in a bad situation and our motivation made a downward spiral.
26	Because everyone was able to go out to the brewery and see exactly what Dick wanted to get done, we were all able to understand the constraints that would eventually drive our design. If anyone had troubles understanding a concept that we were going to employ or a change to the design, it was carefully communicated to them. I especially appreciated this as an industrial engineer without as much knowledge of kinetics. Whenever I didnt understand how a part was going to be attached, Dan, Mike and Matt were helpful in communicating the idea. They also respected my ideas and never once made any jokes about being an industrial engineer (ME's tend to do that).	I had a great group of guys who had no problem getting everything done. Everyone was understanding when someone had other commitments when we were meeting, and everyone was supportive of any ideas that a group member was communicating. I honestly could not have asked for a better team.	I think by the end of the project everyone had a firm understanding of everything that Dick was looking for as an employer, and everything that we knew would make the design possible to implement in a microbrewery with regards to power, space, and efficiency. Through various talks we were able to pinpoint exactly what we would be able to accomplish and what a final product might look like when taking into account all factors and constraints.	Just like what was stated in the previous question, by the end of the project we knew exactly what Dick was looking for. In the beginning, I think Dick knew exactly what he wanted, which was a hydraulic press. We determined that this would not be efficient, but still used Dicks other constraints to work out our final design. Because a forklift is readily available in most microbreweries, I stand strong in that we made the right decision in using it to press the grains. This would make the final product available to more people.	I found the entire process to be extremely helpful and enlightening. Through these past 15 weeks I have grown to both appreciate and criticize the design of everyday objects. I look for possible improvements or changes that I would make. I also believe that the design process is something that I will definitely utilize in the professional world.
27	The main problem was the feeling that we needed to change when we had an idea something or go with something else because we had that idea for a while. We all understood the underlying problem though, so with four minds working together, we came up with a pretty good solution.	We all did equal ammounts of work and quality work at that. We communicated very well also.	More factors could have been explored, but in the beginning of our design careers it's hard to train yourself to think away from the ideas that you already have. After some more practice, we probably could have come from more angles, but for our first timwe I think we did fairly well.	Since our user was part of our group, we got instant feedback, helping us tailor our design to make it optimal.	Our group just did what it had to do to have a quality final product. Everyone came with good ideas and all ideas were tried out. The only thing that I would change would be that we got to our idea a little late in the game. It's hard to change how quickly ideas come up, so that really wasn't that big of a problem
28	I think having a deadline approaching help narrow down our choices most efficiently.	I think we works well together as a team.	I think cost would be a significant problem with our design. I don't think we factored that enough into our design.	I think we had a pretty accurate vision for the direct stake holders. However manufacturing and repair would be a concern we didn't address in our project.	I think we did a good job and had a good prototype. I feel like we needed to work directly with a supplier of our product to figure out some pitfalls or constraints we hadn't initially seen. I think

Continued

Table C.4 continued

					we thought about our product is the larger picture well.
29	The goals of our project were pretty straightforward, and there were not a lot of suggestions that really totally missed the point. Our main task was comparing two ideas, and assessing which was most practical, from a design goal point of view and a user point of view.	Our group really came together, and we had great camaraderie and the final build was pretty smooth. This could be because we had spend the time refining our design on paper before we build, but our final meets were very enjoyable.	We did not have a ton of constraints, and some we added ourselves (such as two bales vs. single) which I feel we did well to consider.	We only had exposure to one user of the item we were redesigning, but the needs of various users don't stretch very far. Obviously, large industrial farms will have different methods, but small scale farmers generally have a truck or towing vehicle, which is all that is needed for our product to work. There are things that i feel we could be missing by not knowing about a wider range of cow-raising farmers	I chose a lower rating mostly because we were unable to realize a lot of our ideas on the final prototype. This is almost completely due to cost issues. For our design, it would be build on more of an industrial scale, with rugged parts and solid fixtures. Building this on a small scale using weaker materials was tough to execute, and some 'stand ins' were required to communicate our idea.
30	I feel like we all had a very good understanding of the problem. I was a member of the group that we were trying to design for so naturally I had a much better understanding of the problem coming into it. I tried to share as much understanding as possible and that definitely helped but it would be almost impossible to achieve completely shared understanding.	I feel like we communicated much better in the later weeks and that allowed us to work more efficiently. We divided up responsibilities and we took initiative for continuing to work on improving the design.	I think we addressed all relevant constraints for the prototype setup that we were working with. Our prototype needed to be adaptable to many different bike seats and I think we addressed constraints individually so that if any one of them were to change it would still work. I don't think we necessarily addressed all constraints if more than one factor were to change because it was difficult to manage all those options and I thought that was not a likely scenario for us.	I am a member of the group that we were designing for so I think that I have a detailed and accurate understanding of the problems and the needs of the stakeholders since I have first-hand experience with the problem.	I feel like we adequately addressed all aspects of the initial problem. I feel like we could have improved the level of integration in the prototype as that was an important constraint in our design. I felt like we did well in not neglecting certain needs to address other needs. In the end everything seemed to be taken care of.
31	Nothing. Group was able to reach a consensus fairly easily.	Worked well as a team - motivated each other to come up with good ideas.	Explored numerous constraints.	Met up with user multiple times to get his input on the design.	I feel that the design turned out exactly as we had envisioned it to be.
32	The thing that has contributed most to our understanding is that we have worked together each part of the way to ensure everyone's ideas were taken into account and everyone understood what was going on with the final design.	Everyone pitched in on the final design. I believe the work load was evenly distributed and everyone brought some ideas to the table.	I think there can always be room for improvement, but with the time constraints and material constraints I believe we came up with a very good solution.	We understood the needs enough to design the product that would meet their constraints and benefit them. However there are still many details that we do not know.	I believe the design is about as good as it is going to get. The next step would be making sure that everything would in fact be able to handle the actual load of two hay bales. If that were to work I think this is a great solution and a dramatic improvement on past designs.
33	Nothing really, we were all on the same page.	We had no issues working together, and no one complained about doing their share.	Due to time, it was difficult for our group to physically test and study our problem in as great of detail as we may have liked.	Pretty well, it was them understanding our options that we had an issue with.	I feel that our design is viable option when it comes to mechanically squeezing the grains, however I didn't feel that our project was able to utilize much of the concepts learned in the class, due to the nature of our project.

Continued

Table C.4 continued

34	The shared understanding was because everyone was part of all the discussion and design ideas there was no segregation of certain design features or product features. Everyone provided insights and critical feedback on what was being worked on and through cross questioning and answering these questions we were able to establish what we were doing why we were doing it and where the product was headed.	There was a constant flow of ideas and a healthy discussion through each stage of the designing and prototyping which shows that the team member were comfortable with each other. It also shows that everyone was thinking independently and questioning each process so that the product turned out to be good and no personal biases were propogated.	As stated earlier there were some parts which could have been worked on more to refine the product and come up with something more ingenious than just a student tablet and productivity tools. However within the given time period I think the group did a good job of exploring as many possibilities and coming up with prototype and walking through the features the glitches and then coming up with safety mechanisms.	We started out targetting only the teachers but ended up various other concerned stakeholders like the parents, students and publishers which encompasses a wide wide variety of people to whom this product targets. Going through each of the stake holders positions and understanding how the product would look from their end and what purpose it would serve as an entire system lead to a really good understanding of the various stake holders and their needs and inturn trying to find a middle ground.	Though the device was more software oriented there were ergonomics that could have been looked into even with what the software did and how it did it. Given that the group was pressed for time I think we did a fairly good job. but could have refined on our ideas more to come up with a product that didn't resemble a mashup of 3 different pre existing products.
35	Good communication matters. For each problem we encountered, we share our personal ideas and evaluate those. This helps to make finalize our design.	It is good overall. But we just had too many meetings some are less efficient. We can solve this problem by email, texting and phone calls.	We concern more with mechanical constraints related to our design because these can not be easily addressed.	Understanding stakeholders' need are fundamental for desigin our project. That is why we came to visit our users almost every week. It is true at first we cannot clearly identify the exact needs, even if we did, we had difficulty figuring out a reasonal solution. So keeping contact with our users becomes more important. As long as we get in the problem, we had a better understanding of user needs. That helps to improve our prototype.	Final prototype gets a lot of positive comments. Compared with initial prototype, it is ideally functional and our users think it could work.
36	sometime the new idea from group member might make things more confusing. So we work a lot on share each body's share	everyone participate group meeting and contribute to the work	we addressed most constraints by change design and materials	I understand a lot after we talk with the person and put ourselve in the situation	I think we build it well as we proposed, but some good design is difficult to execute
37	That we all saw what was needed or missing in the OR.	We all worked hard to achieve something great. We all went over our comfort level to reach a successful design. Two of the group members going to the OR and seeing surgery and blood, wasn't easy, however we did all went.	We have succeeded in designing and making a very good prototype. However i still feel that the design could be further enhanced and improved.	We all have a general idea of what could be done for the stakeholders needs, however, if a final meeting with the USER for more detailed feedback would would give us a more accurate understanding	Class was rally good in general. I learned a lot, to how to design and choose your user and the best design that would suit the USER

Experimental Population Data

	Survey 1			Survey 2							Survey 3								
Student ID	Attitude about design project.	Attitude about quality of teamwork.	Attitude toward CCMT.	Attitude about design project.	Attitude about quality of teamwork.	Impact of CCMT on ideation and solutions.	Shared understanding of the design problem.	Impact of CCMT on understanding of the design problem.	Understanding of relevant stakeholder needs.	Impact of CCMT on understanding of relevant stakeholders, and stakeholder	Attitude toward CCMT.	Attitude about design project and final solution.	Attitude about quality of teamwork.	Degree to which your group's final solution represents a consensus.	Shared understanding of the design problem.	Confidence that all of the relevant factors and constraints were explored	Impact of CCMT on understanding of the design problem.	Understanding of relevant stakeholders, and stakeholder needs.	Impact of CCMT on understanding of relevant stakeholders, and stakeholder	Impact of CCMT on ideation and solutions.	Attitude toward CCMT.	Likelihood of CCMT reuse.
1	3	3	2	3	4	1	5	1	2	1	2	4	5	5	5	4	2	4	3	3	3	3
2	3	5	3	4	5	5	3	3	4	5	5	5	4	5	4	3	4	5	3	5	4	4
3	3	5	2	3	4	2	4	3	5	2	2	4	5	5	4	5	2	3	1	3	3	2
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40	4	4	2	3	4	2	4	2	3	1	1	4	4	4	4	5	3	2	1	3	2	3

Continued

Table C.5: Experimental population survey data.

Table C.5 continued

41	4	5	5	4	5	3	4	2	4	3	4	4	5	4	4	5	5	4	3	5	4	4
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Survey 1 Qualitative Responses (Experimental Population)

ID	Attitude about design project.	Attitude about quality of teamwork.	Attitude toward CCMT.
1	The product, if done well, will really help someone out in day-to-day activities. But there isn't a lot of room to be creative and really come up with some innovative ideas.	Some team members are good at contributing to brainstorming and idea formation, but others are just happy to sit back and not have any useful input. I don't think they are lazy, I just think that they are typical engineers who think more about numbers and equations, and aren't used to creative problem solving.	I really hope that the matrix is useful in improving our project, but I don't think my team members will try to utilize it much.
2	I feel that our current design is not narrow enough so it is hard coming up with ideas that match all the redesign.	My team members all work hard and they keep good schedule times.	Am looking forward to work with it and would like to see where this leads our designs for the better
3	The job shadow helped spark ideas but creating a functional prototype seems difficult.	The team works well together; everybody is flexible with their schedule and puts forth effort.	It seems confusing but once its understood I think it will be helpful.
4	Design is a long process for people and the goal is to make life easier and better. I am an engineer and I am obligated to do that. That is why I keep positive attitude to every design. However, sometimes it takes lots of time to do that and I have lots of other classes, they can be quite conflict.	Everyone keeps working well and we are on the right track to do everything.	The current one is very reasonable and it includes everything and the rank is generated after our meeting and discussion.
5	I'm not very excited about the product that we have chose to design	For the most part we work pretty well together.	I'm looking forward to using it
6	We had a great shadowing experience and generated many possible directions to go. The IV pole is a great foundation for improvement.	We had a very good light project, so I know we have the capability of creating a good IV pole. Haven't really had to come up with any concrete results on this project yet though, so I can't give it a 5 at this point in time.	Haven't really used it on our project yet. We will be doing it this week after we bring together all of the team members' design concepts. I do believe, as stated earlier, that it will be essential in determining which designs are most important for incorporating.
7	We are making progress with design. We have a good problem that is allows us the ability to explore around. It should be interesting to see how all our designs come together on Monday.	Everybody is equally concerned about the project, and everybody is playing a vital part in making the project successful.	I like the work that has been put into it, and I really hope that it helps. It "seems" useful, but I haven't used it extensively yet.
8	I feel that our design is a very good idea. I believe there is a lot of potential in or project. There really is not a good way for scuba divers to communicate under water.	Everyone does their fair share and contributes well during meetings.	It is a good idea. As of now, I am not sure if it will work as well as I hope. This is mainly because my design focus seems a little broad and it is hard to come up with constraints that fit all of my design ideas.
9	As we haven't even looked at each others design idea yet, I am basing this completely off of what we haven chosen for our project. We chose to redesign the hospital gown and I am very excited about it. There seems to be a lot of different things we can target and redesign on it. I am looking forward to the design process now.	I think we have broken up the work well so far and done things efficiently.	I think it will be very helpful, but I am a little worried the time put into populating it will not be worth the pay off.
10			
11	I'm excited about our project. I feel like our group has good chemistry and has a lot of great ideas.	Everyone contributes pretty evenly.	I look forward to seeing how this will effect our group's project.
12			
13	I am excited about the design project and looking forward to the experience that I will get from completing the project.	I feel that my group works very well together, however, I think that we need to be more pro-active with our meetings and goals in order to be where we want to be by the end of the project.	I'm very optimistic about the constraint matrix and its utility with regard to our design and look forward to what it tells us about our design.
14	I am excited about doing this project and I think from the user we picked we have a lot of potential to make a	I like my team and I think we work well together. I think everyone feels comfortable generating ideas	I think it's a good thing to do for this project but, ordinarily i would probably do something much more

Continued

Table C.6: Qualitative response data for experimental survey 1.

Table C.6 continued

	quality design. At this stage though there's a lot left to do and we haven't really made any solid decisions that define our project, so it's hard to see how it will all come together.	together, and we have open effective discussions. The work seems well distributed. The only problem I predict would be finding time we can all work together and managing time so we get everything done.	basic. I think of it more as an assignment I have to do than something that will be really beneficial to us.
15	Not quite sure where we are going with it yet... I'm a little scared of the potential complexity of the product.	We always meet deadlines and are always on time to meetings, etc. The only negative part I think is that we are all too agreeable with one another.	I think it's a good idea for us to assign value to our constraints. It will help us narrow our focus on certain constraints, while also getting a broad view on how each affects our final product.
16			
17	I really enjoy this product design class. It relates a lot of what I did on my past intership, knowing that this class (projects and lectures) have a real world application keeps me motivated and enthusiastic about the project.	We work well as a group, everybody takes criticism in a positive way in order to improve our designs and come up with a good design.	Not sure at this point
18	It is still in the beginning of it and I am excited to see where it is going.	Overall has been good, but there hasn't but much to do yet either.	I think it will be good over all, I just haven't seen one as complicated yet.
19	It may very difficult at this point to come up with a quality design due to complexity and time constraints	We work well as a team but have had difficulty meeting due to conflicting schedules. Most of us have multiple projects going on top of classes, jobs, or interviews.	Kind of early to have any real opinion about it but I believe it will be helpful.
20	This is education I don't get in other classes and I feel that it's extremely applicable and "real-world." Working with actual users and getting free reign of our design decisions from the ground up are the best parts.	I know both other members outside of class and we work very well together. Everyone contributes equally as well as having unique perspectives.	I am neutral at this point and will need more experience using it before I can really give a good opinion.
21			
22	We went and shadowed an pediatric patient outcare center (at Nationwide). We spent a solid 2.5 hours there shadowing a doctor and talking with a nurse. We identified many opportunities that were beyond the scope of this class, and finally settled on redesigning a hospital cart for the patients to use as they come in. It just isn't a very exciting concept, but at least it is a direction to pursue.	The group is ok. Two of us seem most motivated and task oriented. One has good ideas, but not good on follow-through. And one has terrible ideas and seems unable to contribute in any meaningful way.	I think it will be a valuable asset in forcing our team to thoroughly think through all aspects of the design.
23	Researching real users is almost always an interesting and valuable experience. We're in the concept phase right now. Anything could happen so it's exciting.	For the most part our team functions well, however, it is quite challenging to find a meeting time outside of class that works for all 4 of our schedules- it slows down the progress. It's challenging to do research or any work together. I find myself doing a lot of the design work (sketching, graphic layouts, prototypes) for our team which I expected would happen since I'm the only designer in a group of engineers. I enjoy it, however, I would like to spread the work load out a little more evenly.	I'm hopeful that it will be useful to us.
24			
25	I'm interested in how teams work together. In that light, I'm learning to pick my battles on which ideas I really care about. I'm optimistic that we'll end up with a good product.	Although it's necessary to fight through each idea, our product will come out great because of it.	A constraint matrix should help us with different design decisions.
26	I believe that we have a great starting point, but after looking into some of the products we have conceptualized, a lot more work must be put in to making these work.	We work great together. We know when to work hard, and we do not goof off when we are trying to get work done.	As stated before, our devices that have been conceptualized are simple, and most constraint relationships can be visualized.
27	I am excited to begin coming up with ideas and seeing my teammates ideas.	everybody does their share of the work	Not really sure how I feel about it before I have used it.

Continued

Table C.6 continued

28	I enjoy going out and finding a real-world problem to solve. It would be nice to have a better idea of the total scope of the project, knowing all future assignments and deadlines at the onset.	Team members have been passionate about producing a quality product and have been reasonably good about meeting on time.	I think it will be a useful tool for the team to speed the design process, but it will not necessarily have an earth-shattering impact on the final product.
29	I feel that a good foundation has been laid out for our project but the areas available to us for redesign are more limited than I would like. We have access to an area which should provide plenty of design opportunities, a pediatric clinic, but so far have only found a single area we can really focus on for this project.	I feel my team works very well together and the quality of our work is top notch. I have no complaints about how we perform in this area.	I am excited by this tool but uncertain as to how effective it will ultimately be. Having not used the matrix yet in determining acceptable designs I do not know its effectiveness. Further use of this matrix in narrowing down on real design solutions will perhaps change my mind.
30	I'm enjoying the process so far.	We had some scheduling conflicts so far, but overall it been pretty good.	I think its a good tool to thinking through what constraints are affecting the design and how all of those constraints work together. The excel program makes this process much easier by changing all affected cells once one cell is changed.
31	At the place we are now, I think we have some interesting leads, although this attitude may change in the coming days.	I think we're doing a good job of building off of other people's ideas, but in some situations we can tend to interrupt or cast down some ideas potentially too early.	It sounds like extra work.
32	We've been unable to conduct our surveys, shadowing, or interviews for three weeks, our product will likely rely on electronics and software we can't emulate, and our target customers are likely to have a difficult time evaluating our prototypes (and will be difficult to evaluate themselves) due to age/mental issues or else with HIPAA and drug regulations.	We work well together, stay in good contact, everyone seems to complete their responsibilities, and have a variety of skills that complement each other well. Everyone has a good attitude and work ethic, despite the state of our project.	Tentatively hopeful, and impressed with the excel programming that went into it. I was especially interested in how it detected and highlighted second-order interactions, which I think will be a very useful feature.
33	I enjoy thinking of new ways to get past obstacles and we are designing for a bicycle which I personally enjoy using and that makes the project more interesting for me.	There are only 3 of us but we all communicate and work very well together and are never afraid to throw ideas out or ask questions if need be.	I am excited to try it out because we did learn about how it can be useful in class and I think it definitely has potential to make our design better as well.
34	I am pretty neutral on the design project. As of right now, I think we have a lot of good ideas going into the ideation step of the process. That being said, I am interested to see where it goes from here.	I think my group's teamwork has been good so far. There are a couple flaws that we need to work on. An example being meeting times to work on the projects. Our schedules do not match up very well.	I think the constraint matrix will help us with more ideas for our project.
35	I'm not overly excited about our design opportunity, but I don't hate it either.	Most of the group members fully participate in every meeting.	It is a good tool to help focus our time on the important details of the project.
36	I feel like the group is very excited to further pursue our light design idea. We would really love to have it workout where we could pursue to the patent phase. We have also been enjoying the class and find what is being taught in class and in lab very helpful.	Again, the group is excited to be working on our light idea to try to further it to the patent phase. We are all on a similar page and putting forth the effort to keep the group moving in the right direction.	We'll see if we can capture all of the design aspects in the matrix. If we do, this tool will be very helpful in the design process and exposing areas of improvement.
37	Good design project, one thing that I am not used to is having such an open ended project. For this project it was difficult to pick a group of people to work with but once that was decided the project seemed a lot easier.	Good teammates. Usually meet outside of lab once a week as well as meeting during the lab time. Work among the group members is usually split up pretty evenly.	Kind of still confused about it, but I haven't looked at it very much yet. Will probably make much more sense once I try to use it.
38	I'm definitely interested in the project. It is though to make sure to set aside enough time with other classes and obligations for doing everything I want with it, however.	Very good. We work and communicate well with each other.	It's tough to make good use of it this early in the process of getting used to it. It does seem to have potential to be useful, so we need to put more time into refining it. The example is useful for reference.
39	I feel like our project (lighting for police officers) can provide immediate and tangible results for the real world.	From previous work this semester I know this group is capable of doing good work.	It looks to be a very useful way to organize information and I look forward to using it over some other matrix I would have to draw myself.
40			

Continued

Table C.6 continued

41	I believe we have a great idea that can actually help how new hospital gowns will be designed.	Everyone is always on the same page and everyone contributes.	It is a great tool that is easy to use and understand. I believe it will make are design better then it would be if we did not use the matrix.
42	We have talked to people involved with scuba diving and they have explained the difficulties of the area we are hoping to work towards. It seems like we are moving forward and have a definitive direction.	I feel that our group works very well together. We have one group member who leaves our meetings whenever he wants, regardless of whether we are finished with our work or not, which is a bit frustrating, but other than that things are going very smoothly.	My only experience with the matrix is the Paul's explanation in class, so having not actually used the constraint matrix yet, I have no feelings towards it.
43	I really enjoy the different aspects of the design class in comparison to the other mechanical engineering curriculum.	Our work is efficient and each member offers different insight into the design process.	I feel as though our group knows the direction of where we want to go before the constraint matrix, but feel it will be helpful in more complicated decisions.
44	I am excited about the project but I do not have the time to complete this project to the standards of quality I would like. If this was one of only a couple classes I would have more time to put in and as a result I would feel a lot better about the end product.	We all knew each other fairly well before hand so we trust each other to get work done.	It should be helpful but I feel like I am more indifferent. I think the main reasoning everyone choose to use it was to not have to have a final report. I'll be interested in seeing how much all the groups gain from the matrix
45	I am currently enjoying the project, but the difficulty of finding something to redesign was not desireable.	I feel as though that our group communication is excellent and we could go far with this project.	have not really messed with it just yet, but i feel as thought that it will helpful
46	We are dealing with an interesting problem but the solutions are more limited than I initially expected.	Everyone is completing the required tasks.	I expect that it should be helpful.
47	I have confidence that my group can come up with a novel idea that at least on paper, has real world application potential. The challenge of taking creative ideas and turning them into practical concepts can be rewarding.	My team wants to work together cohesively but for now, communication and scheduling is difficult and a fair amount of work is accomplished individually.	The consrtaint matrix will take additional time but should be helpful in the design process. Currently, I believe the benefits will outweigh the extra work.
48	Identified bunch of usability issues with the user (cop).	Constantly in contact with the user and following up with him. Positively involved and trying to understand the existing issues.	Will help in precise understanding the constraints and their interrelationship.
49	Busy with job interviews and other school work	We have busy schedules so sometimes it is difficult to find good meeting times	Still learning how to use it
50	It's a great opportunity to go through the design process from start to finish. The shadowing was a great experience, very inspiring.	Having an issue with one member contributing but it is mainly do to conflicting schedules.	seems like it will be a great tool
51			
52	I am having trouble coming up with the 15 required ideas, but I am looking forward to coming up with a good prototype.	We work well together when people are able to meet. There has been times where people have cancelled right before we were about to meet. This makes it very frustrating for the rest of the group that would like to move forward.	Right now the design matrix is just an extra item that needs to get accomplished and it has not benefited us yet. So my current attitude toward the matrix is not very good.
53			
54	I feel that there is a lot of room for growth in the redesign of the portable gas tank. It is also a problem that I have dealt with, which makes it easy to relate to.	I am happy with the quality of how my team works as a group. I ranked this a 4 instead of a 5 due to having other group projects in which all of the members seemed more eager to work together compared to this group. However, I have not had any problems or issues with my team and we have been able to work well together.	I have not started the decision matrix yet, and I know that I will have to put a good amount of time into it to come up with all of the constraints on my design. However, once the initial process of adding the constraints is over, I believe that the matrix will be very helpful further in the design process.
55			
56	The design product I am working on is interesting but it is a very common topic at the same time. A lot of people might have worked on it and it becomes difficult to stand by the expectations of the TA and the Professor.	I have a very awesome group. Thanks to our TA for that. We work as a team and enjoy it.	Undoubtedly, a good design comes from a lot of constraints.

Continued

Table C.6 continued

57	Would be more interested, but have too much of a workload from other classes.	It is good, not much communication out of lab though.	Looks confusing and looks like it requires a lot of time to fill it out properly.
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Survey 2 Qualitative Responses (Experimental Population)

ID	Attitude about design project.	Attitude about quality of teamwork.	Impact of CCMT on ideation and solutions.	Shared understanding of the design problem.
1	I think that we have good ideas of how to solve our problem, I just don't know if we have the ability/resources to accomplish those goals.	We did well with our first prototype by trying to communicate our ideas to the class. It is difficult to imagine a person using this device without actually seeing it for yourself, but I think we got the point across well.	I'm not even sure how those two correlate.	I think our team understands project very well. Everyone seems to be on the same page as far as what to do next and what our final goal should be.
2	Still trying to get on the same page with all the group members, had another idea on where we were going then had a change in the plans but I feel this new idea will allow for us to design a better produce.	Our group is very anxious about this project and the designs that we can come up with.	I has shown us who our stakeholders our and what constraints each one of them require on the the produce.	Our group had another problem that our client wanted solve but because their is not real way of coming up with a produce for it we are now switching gears trying to all get on the same page.
3	Right now there is a lack of interest in the product being redesigned since I have never used it before nor will I in the near future. However, since the project requires a complex solution it is still fairly interesting.	So far the group has produced quality work but it is hindered by the materials easily available for prototyping. In terms of teamwork, the team works well but typically follows the ideas of one member who has a more dominant personality.	The constraint matrix has not impacted any of our ideas thus far.	Overall most have the same understanding but ideas don't always get fully communicated to everybody because of their complexity.
4	In order to make the police officer have a better working environment and protect the community, I would happy to make efforts.	The team work is ok. But when come to meeting times, they always change the time that we previously set. That makes me very uncomfortable. I am not very flexible for that.	If we are asked to make a real prototyped radio system, it could be very hard because we have to design the control of the radio staff, which is out of our capability. But if we just design the shape and button, that is not a problem.	We are redesigning the radio system by lower the number of buttons and changing the functions. The idea is simple but the process would be hard.
5	This is a difficult product to design so there isn't a clear vision and that makes t not as fun since we don't know if the direction we're headed down is he best choice	It's a bit difficult to get everyone together for a long period of time, due to conflicting schedule	It had little impact on the physical design/function of the product.	I think what's helping us is our understanding that we must focus on the user and not so much the physical/manufacturability of the product. What is hindering us is our lack of vision of how the product sustainably differentiate from others on the market.
6	Very fun, good imput from our nurse that we shadowed.	All 4 team members are contributing a lot and equally becauase our project is interesting.	Created matrix after we built the prototype. We will be go back and iterate though .	This is a very modular design so we are able to each come up with different ideas that don't conflict with one another.
7	I am optimistic about our design based on our work so far. I think that we have some good ideas, some good class input, and I am looking forward to cranking out our final design.	Everybody gets along. Work is apportioned as appropriate. We all find times to meet up when necessary.	It has helped with giving us an idea of what to focus on and what to put less effort on in order to finish our project on time. For example, because of the constraint matrix, we are able to say that "mobility" is one of our largest constraints, and we must therefore work effectively to increase mobility in our design from existing designs.	Everybody's willingness to work together to get the job done and everybody's understanding that at the end of the day, we are building the IV Pole to reflect concerns voiced by the nurse that we met a few weeks ago makes us all great contributors to the team.

Continued

Table C.7: Qualitative response data for experimental survey 2 (part 1).

Table C.7 continued

8	I really like our design idea. I believe it has a lot of potential. Everyone we have spoken to in the user group have had something to say about their struggles communicating under water. Also, looking at the competition it seems very possible that we could come up with a good alternative to what they already have.	Everything works well when we are in meetings. Everyone contributes and gives good ideas. One member hasn't been showing up to all of the meetings though and that can be a little frustrating.	It has made us realize different design constraints to think about and how the constraints relate which is very important, but we haven't focused enough on how it could help. We have been more communicating with each other to see what we think is best.	The fact that our design idea is very broad has caused some debates on where we should go next. We all agree on our main idea and what we should be going for, but there are arguments about how we should do it. Some group members do not want to make something too complex where as others want to.
9	I have really enjoyed it, but designing as a group (as opposed to individually) can be very difficult.	I think we are doing very well, I am happy with the features that we have designed. I will be more confident in saying that (or perhaps not) after our first prototype presentation tomorrow.	I do not think it has impacted things too much. As i said earlier, we essentially designed the product as best we could, and then went back and filled out the matrix as best we could from what we designed.	I think we share a very good understanding, we haven't had problems with that at all.
10	It is a very stress free project that teaches us about a solid design process/project. However, we know that we need to stay on top of things if we want our design to be successful.	We all work together cooperatively and the mood is always light and fun when we are working. Everyone is always willing to participate and help the group in whatever means necessary.	We still need to evaluate our matrix in order to see the impact the completed matrix has on our design.	We always work together on which ever project task is at hand. Everyone listens to the others ideas and takes them into fair consideration.
11	I'm optimistic.	I feel we are working towards our goal in an effective manner. We still have a lot to consider at this point, however, we are all positive.	Not much, we did most ideation apart from the matrix.	We almost all have a complete shared understanding because we have very good open communication and if a member cannot come to a meeting, we make sure to completely fill them in.
12	There are a lot of constraints and I think it will take more trial and error as well as research and interviewing to tackle our challenges with this project.	We found many obstacles in the usage of the "Forearm Forklift" straps (the main part of our current design through actual testing/carrying of heavy rigid objects such as carrying up and downstairs as well as the necessary balance needed to be achieved with a 3-4-5 triangle and balancing of static equilibrium and moments. This would be much harder with an uneven distribution of weight of a typical obese person.	We have yet to use the matrix to its full capacity since we very recently began to use it.	I think just our backgrounds and knowledge has both contributed and hindered our shared understanding. It is good to have such a broad idea generation but at the same time it is sometimes difficult to really accept each other's concepts without some groupthink.
13	I am optimistic about the design but have initial doubts about the specifics of the design and electronic components. I understand that these can be overcome, but my initial thoughts are cautiously optimistic.	I think we have done some good work and research, but not up to our potential. With the lightened load of classes for the 2nd half of the semester I expect that the quality of work will imporve.	The ability to see what is most important/least important factors and their relationships has allowed us to more precisely design the product to meet those needs. All in all, I would say that is has been of great value to the design process.	I think we have a good understanding of what is to be done and what we have to do to get there, but the day-to-day tasks could use some imporvement since we find ourselves with a plan but typically no immediate tasks.
14	After completing the first prototype I think we've done a good job so far at addressing the issues and I think if we can fine tune what we have our end product will be good.	The work we did building the prototype wasn't well balanced between the group member's but that was mostly due to us being unable to come up with a time that we could all work on it while the shops were open. It would help though if other group members stepped up more and tried to arrange times that they could participate.	It's got me thinking about how different ideas will affect the stakeholders and alternate parameters, but I haven't really used it to evaluate features and decide what to use.	I think the more time we all spend together discussing what's important the more we all understand what our focus is.

Continued

Table C.7 continued

15	It is a long road ahead. And after seeing where others are at, I feel like we need to step back and look at this whole problem in a different way.	Has been a bit of a disconnect recently. I guess we all didn't share the same vision. But after class today I feel a lot better.	Has not been used as a design tool just yet.	Our persona was not well defined and we overlooked how the features would interact. Our persona was based on the person we shadowed, but he is not an extreme user. By making our user more extreme, I feel like our product can benefit those in less extreme situations.
16	I like the idea and the project and I am learning a lot. But it is not coming along nearly as well as I had expected.	We work fine together, but some have forgot about meetings and not been asking to contribute.	It had a pretty big impact because I actually thought of different solutions while considering constraints.	I think we all have a good understanding of the problem, the biggest thing for us is what user group we are focusing on.
17	I am motivated, the fact that we can create a tool that will help people (handicap) to perform activities in an easier way than they normaly do.	We are motivated which is an importatn factor to have a positive attitude. Our goal is to help people rather than create a product that is intended to be a market success.	At this point not very.	Shadowing a potential user of the product. Getting her feedback about our ideas and her recomendations.
18	Overall going fairly smoothly	We work well together	Let us see how to integrate the parts.	We communicate our thoughts till everyone is on the same page.
19	It is improving. We have made some good progress this last week with the prototype but it will continue to be difficult to find meeting times and work on the project.	Improving. We were able to meet more frequently this past week and made some good progress. This allowed us to have more confidence in our efforts.	We filled out the matrix before coming up with all of our designs. Because of this, we had the constraints in the back of our mind when coming up with ideas and many of the concepts turned out to be fairly solid starting points.	We are all on the same page as of what needs to be done and what we are all doing to get the project done. We have managed to communicate very well so we can stay updated on our project even if we are unable to meet at a given time to go over the next step or process.
20	I think its a great study of the design process.	We work really well together.	We didn't fill it out until after we had our concept in mind.	We communicate well and ask each other a lot of questions, so were on the same page.
21	It is positive because we are moving forward but the farther we get involved in the project the more we realize that we have to take on. Originally we were just going to design a new mirror and now we have expanded into designing a foot control for the mirror as well.	Everyone is contributing with their different abilities.	It has help us visualize the interdependence between all the constraints, mainly the physical constraints.	We have not all been able to meet with the dental students. I have personally met with both dental students we have been using but no one else has because of scheduling difficulties.
22	I hate it. Dumb product, forcing ourselves to keep "developing the idea," even though it's a poor idea in the first place.	We have chosen a difficult product to be creative and novel with. So the team isn't happy about that in general. If we had unlimited time on our hands it would be better for us to try another shadow and choose a different product. However, we don't have that time and must push through.	We have not utilized the matrix to any significant extent yet.	Creating an ideal solution that is different than other products on the market is proving to be challenging. We are stuck on an idea that seems best, but is very similar to a ergonomic version of the modern shopping cart.
23	The problem of moving obese people in fires is a fairly common problem and it's pretty exciting trying to come up with a solution.	So far we are working well as a team.	We didn't fully fill out the constraint matrix so we haven't utilized it as much for the design solutions.	Talking with our user (firefighters) has helped us to move forward as a team as well as trying things out together with our prototype.
24	I truly believe we can make a great design and take advantage of every tool we have learned, including the matrix!	All of us care about the project, but we all have a lot of responsibilities. I just wish we had more time to work as a group and not individually at home.	We haven't worked as closely as we would like on the matrix.	Since we all use dumpsters and have seen the problems that it has, it's easy to share an idea of what needs to be done, the relevant factors, etc.

Continued

Table C.7 continued

25	It's good to get group experience when debating different problems.	Besides some fundamental differences on whether the way a button is pressed matters (whether it should be pressed or held) our group is collaborating well.	In this class, it hasn't impacted our design solutions because we don't deal with manufactering or assembly. Our product won't actually get made and we don't have the experience to say what designs work better one way or another for the manufacturer.	I think our team is still designing more for themselves instead of our base user. We're still coming up with good ideas for each user group.
26	As said before, we have come to hurdles and have not been able to generate new solutions to it, so we have become slightly discouraged.	Seeing that we have such a tight constraint with the size, and we have been struggling to generate ideas to overcome the size restriction, we are starting to slow down and become discouraged.	We did the constraint matrix, went through it, and saw that there were no new interactions that we did not understand.	I believe that we are all on the same page. Any time we have done design changes or prototypes, we have always been together.
27	It is interesting and I believe we can create a legitimate prototype.	WE all work fine together.	It helped us decide the actuation device and whenever and aspect was brought up we used the matrix to locate what it would effect and what other aspects it would effect.	We try to email and communicate whenever necessary and make progress each time we meet.
28	The firefighter team that we are working with (Grandview Heights Station 51), has been fantastic and very accommodating to our project. I am excited to make something useful to help them in their job duties. I feel like we have chosen to tackle a very difficult problem (moving obese victims) and am nervous about how we will get to a great solution.	All team members have a desire to make the best product possible. Some members are far less likely to compromise than others when it comes to deviating from the original vision of a solution.	At this point in the project, the constraint matrix has only moderately guided our initial design solution concepts. I expect that as we continue, it will play a bigger role in fleshing-out a detailed design.	The team has acquired a good understanding of the problem definition, mostly due to visiting the Firehouse and trying various equipment hands-on. The group is currently hindered slightly by a desire to jump to a solution too early without attempting to follow the same design process structure used in the first (light source) design project.
29	Confidence in the final design little but of guilt for not offering enough in the product construction. I have belief this final design will work out though it's not quite there, i was also working the day the prototype was made and so missed out.	The team really came together and cooperated to get the inital design done. There is also good cooperation on how we should proced with the design.	The matrix has helped us focus in in what the key needs are for this design. It however has not yet led to any design breakthrough on its own. By this I mean the matrix has helped frame the problem being adressed more clearly but has not led to any specific solution.	There is a clear idea of where this problem should go but not how it should get there. We understand how this product should work but not the specifics on how to make it work.
30	I think the design is a challenging one, but I think we'll be able to come up with a valuable solution to the problem	We are working well together and we're all adding our own input to the final solution.	I think it helps with combining all our information, but it hasn't had a profound effect of the design.	I think our regular meeting are a good way for us to all stay on the same page with the project and continue evolving our idea.
31	I'm excited about where we can take our solution	we're doing well to discuss various solutions to the problem at hand	It's a little weird because for our different solutions that we have now could have different constraints and to pick one or another right now seems sort of restricting	We think similarly about our understanding of the design problem and we also agree that we perhaps don't know all of the relevant factors
32	Our interviews have revealed that our instincts were generally correct and that we were on the correct track. However, the solution we want to make will be impossible for a semester project and difficult to implement on a broad basis, though it would be exciting for our stakeholders. I suspect there are other reasons why some of our solutions have not been implemented in the market, and I'm concerned I do not know what they are.	We are working well together and distributing tasks well. Scheduling and coordinating free time has been difficult at times.	The matrix has been helpful keeping constraints in the forefront of our minds and checking for interactions. Though most of them are things we already knew or considered, it's helpful for offloading mental effort.	We seem to be on the same page, and there is broad consensus on most things. When there have been disagreements the group has been receptive to differing opinions and open to changing paths with evidence. Most discussions have been quick and decisive.

Continued

Table C.7 continued

33	I am a bicycler myself and so I can also relate to this design which is cool to me and in general I enjoy going through this design process hands on and knowing that this product could greatly help someone out in the future.	We communicate very well it is just that at this point in the semester we are all very busy and meeting during free time has become more difficult but I am still very pleased with how well we have worked together through all of it.	As mentioned we just recently filled out the matrix but I believer once we look it over as a group many more ideas will become clearer to us because of how easy it is to look at what constraints are related to what and how important they are to each other.	As mentioned before, conflicting schedules has made meeting more difficult so that has hindered our communication and shared understanding to a degree but I feel like we still all share our ideas and concerns very well together and we all are on the same page with this design.
34	I think we have a lot of good ideas and our project is headed towards a good route.	I think our group is working well as a team and coming up with good ideas.	The matrix has contributed a bit towards our ideation.	I think we are on the right track and will come up with a good design.
35	It's stressful at times but we think we can have a successful design eventually.	We're only getting significant contribution from 3/4 of our team.	Thinking through how different constraints impact each other is more helpful for me than filling out the matrix. It is a similar process, though.	We all have different ideas and sometimes have difficulty agreeing on one.
36	It is coming along well. We have a very good idea and the group is in the process of refining the idea further. We have a very good visual prototype and are in the process of determining how we are going to manufacture a working prototype to put in the hands of police officers.	As with the last survey, the team is excited to be working on this project and would love to take the project through the patent phase.	It has impacted it a little, however the face to face meetings with police officers have influenced the design significantly more.	We have been working with this project almost the entire semester. We have also all been present at almost every meeting and have very open communication channels within the group.
37	Our prototype seems almost functional and will hopefully be something that the user will enjoy to use.	Our teamwork is good. We all did separate parts of the prototype and then came together and discussed the constraint matrix for our product. While the quality of our prototype isn't fully functional it is pretty good for a first prototype and can be used to show our user and get feed back.	Didn't have much of an impact on the first prototype. We will look at it more closely for the final prototype.	Kind of understand it. The matrix thing is still confusing but we attempted to figure it out and are hoping to get some direction in lab tomorrow.
38	Provides an interesting real-world-like learning experience.	We work well together, even with our busy schedules. Our next major focus is to built a more advanced prototype and get it in the hands of a police officer.	Because we have just finished it, it hasn't impacted our design too greatly yet, but it appears to be a useful tool that ultimately will guide us in the rest of our designing.	We keep each other in the loop with any updates and communicate well with each other.
39	We are advancing well on the project and I am confident in its success.	My team works very well together.	The matrix has helped us solidify which factors we must maintain in our final design.	We are all very open minded and conscious of factors important to the success of the project, so working through roadblocks has been very easy.
40	I am still enjoying the process of solving the user's problem with a working prototype.	I believe we have and will continue to work together to produce high quality work.	Our group has used the contraint matrix in a very limited fashion.	There was a difficultly when it came to choosing a product that would be a good project for the class and choosing a product that our user most wanted redesigned.
41	I am excited to pursue this issue with gowns and see want new things we can do.	We always meet a couple time a week and have thought of an issue that many other people have not tried to tackle. We have come up with some great concepts.	We had most of the designs ahead of filling out the matrix but the matrix had us come up with some new ones.	Are ability to meet a couple times a week and have direct communication with our user.
42	I feel the project is progressing in a good direction. We are constantly thinking about the problem and how we can solve it in different ways.	The group works well together, but sometimes one person will get stuck on an idea and will not yield to will of the group.	So far, the constraint matrix has not really impacted the design solutions. The group has just completed the design matrix and we are just beginning to understand constraints and how they affect each other.	It seems as though some members of the group wish to go with a more complicated solution when a simple solution will work just as well.

Continued

Table C.7 continued

43	I really believe that we will produce a working, effective product for our current design.	Our group is on the same page and always completes assignments in a timely and efficient manner.	The constrain matrix was effective, but I believe that our group put in time before hand to understand which designs we believed would be effective.	I feel that working through the constraint matrix resulted in a lengthy discussion of every aspect of our product we are designing. It allowed us to hear different perspectives and work out which factors were the most important.
44	A pessimistic mindset is probably not ideal for a design project but I am a little uncomfortable with where we are now and I am hoping we make some progress in the coming weeks.	I think we are working well together but are struggling with our design, and coming up with any true breakthroughs	The design matrix was not use during our brainstorming for design solutions. It mapped out what we needed to address but I don't know if we creatively spawned any ideas directly using it.	I think we share the same understanding but I do not believe our teams understanding has completely grasped the problem at hand.
45	I think we have a great idea, but i feel as though we wont be able to test our idea on actual patients due to it not have used before ever. We would not want to indanger a patients life just to test our product.	We have met a few times, and are not afraid to disagree about certain ideas. We have had long discussions about certain designs.	Yes it has sprung discussions on what parts of the design we need to look at, but it hasnt changed our design ideas in general	One thing that has hindered our group to be more involved is that some of us have been in the situation (as in the hospital) where certain ideas that we had could have made our visits a little more pleasant.
46	This has been a useful and interesting design project.	We are doing a good job of dividing up the work.	It has helped to focus design solutions, but has not had a large effect.	All of the members of our group use dumpsters so there is a good understanding of the design problem.
47	It seems we have a target problem which is well defined and we have a few different ideas on how to tackle the problem. I believe that the group can combine the various opinions and ideas in order to develop a useful product.	Everyone was able to contribute constraints to the constraint matrix. Individual group members had varying opinions on the weighting of constraint relationship effects but the group was always able to come to a consensus.	Thus far, the constraint matrix has had little impact on our ideation or solution. The ideas which the various group members have envisioned already addressed the constraints and constraint relationships organized in the constraint matrix.	While the group as a whole understands the object that we are designing, I feel that there is a disconnect in the understanding between what would a perfect product look like and what would a practical product look like.
48	have a lot of diversified ideas about the product.	everyone in involved and we had some decent 15 ideas from each of us.	Not yet	frequent meetings with the user and try to understand the existing issues with the product.
49	Our group has a lot of good ideas the challenge right now is exploring the different options for the concept we have agreed upon.	Our group is very busy, hopefully it will be easier to meet as the semester slows down for everyone.	It helped us to think of everything, but we didn't use it for coming up with our initial sketches	Having only seen the problem we are designing for once makes it hard to remember all of the factors that play a part
50	excited for class feedback as well as receiving feedback from the user	everyone is putting in the equal amount of effort and showing up for every meeting	as of now, not much	we share the same goals at to what needs to be accomplished, as well as prioritizing certain components against others i.e. the communication prototype did not need legs or painted--the point is to show the two-piece sliding stretcher.
51	We haven't zeroed in on a solution but I think we have a lot of good potential ideas.	Everyone contributes with ideas. No significant clashes over design constraints or over the general direction of the project so far.	It helped us rule out a few ideas that didn't hit on a constraint that we deemed very important in the matrix.	We haven't narrowed in on an exact problem yet so we don't have a complete shared understanding. However, we all seem to understand the general direction when discussing it in class.
52	I would like to be more ahead in the construction of our final prototype.	Work well together when we can find time to get together.	It has shown us some areas where we can improve our design to develop our design more.	The ability of our group to find enough meeting time for all of us to discuss how to complete this task.
53	The final prototype is a long way off, but I think we'll be able to construct it without any major problems.	Everybody has been willing to meet up and help out on group work.	We just haven't used the matrix enough for me to make a good call on this one.	We were only able to have 2 group members attend the shadowing. This will most likely change in the near

Continued

Table C.7 continued

				future, as we are going to bring our communication prototype to paramedics to get their opinions.
54	I think that there is a lot of room for improvement with our product that our group is willing to put the time into in order to come up with a viable solution. This might be something I would be willing to continue outside of this class if I make some time for it.	We have been able to actively make progress on our product's design. We have open conversation and are able to bounce ideas off of each other to reach a common goal.	It has slightly influenced some of the usage constraints that need to be focused on.	Having us all agree on the original product idea that we needed to focus on allowed us to all move forward with further understanding the problem and what we need to do to fix it. Having us all be comfortable with working together and with making further suggestions also helps a lot.
55	It is a very good hands on experience of the design process.	Everyone is involved and willing to work hard on the project.	It is easy to compare many important aspects of the product. It also allow to analyze its interactions.	It has been very easy for us to make decisions about what is needed to be done. All of us are in the same page.
56	Today's lab session has lowered my moral but I am sure we will make a good comeback. My group is lagging behind as of now but we realize where we are lagging behind and we're gonna work on it.	Our attitude is very positive but it looks like our ideas are very scattered which is refraining us from giving our best. But we have a solid plan now and we will definitely come up with something fantastic.	It has definitely let me realize the constraints associated with our product. And ideas and solutions come from constraints. I already have few ideas generated while working on the matrix.	The main thing that contributed to our group's shared understanding is that we all are bikers and very clearly understand the problems a biker has to face. The thing that hindered our shared understanding is that we don't think at the same level as to what idea is feasible and what is not. We have really good ideas but it is very difficult to convert them into a prototype.
57	Our team encountered a real world problem and our solution is ideal and feasible.	Team work is very good.	Little impact other than showing us some stakeholders.	I think the group has a clear unified understanding of the problem at hand.
58	We are making good progress on the design solution and have a good amount of time to fine tune a few details before building the prototype	Everybody is engaged and enthusiastic about the project	I feel that most of our solutions have been derived without the constraint matrix involved.	We work together to make sure we are all on the same page of the design process.
59	Exciting yet challenging at the same time.	Right now we are at the hardest step of the process but everybody is putting in much effort and thinking beyond the box.	It has helped us in terms of constraints and how we can address that.	Different opinions of important issues.
60	Seems to be a very interesting project that has some bright ideas behind it. Although at this point our group found a few different problems with the initial design that need to be addressed	Everyone contributes a wide variety of ideas and is very flexible when it comes to working together with each other to come up with the best ideas that takes everyone's thoughts and put it all into one.	The design matrix just sort of reenforced most of the problems and stakeholders for our product.	I feel like all of our group members understand the idea of the product we are trying to design but they also like to think outside of the box and are afraid to stretch the constraints to solve the problem in the most innovative way.

ID	Impact of CCMT on understanding of the design problem.	Understanding of relevant stakeholders, and stakeholder needs.	Impact of CCMT on understanding of relevant stakeholders, and stakeholder needs.	Attitude toward CCMT.
1	The design matrix hasn't helped us that much because we haven't really considered many constraints other than usage constraints. Market and technology constraints aren't really a concern for us, and we don't need a matrix to tell us that changing the handle diameter is going to effect our products physical size/footprint.	Again, our main focus is the end user. We probably need to put more time into thinking about the Manufacturers as a stakeholder, but at this stage the looks of the project are still changing rapidly.	We haven't given much thought to it.	Its a neat tool to have, but it hasn't been much use to us yet.
2	Our group had a set back and because of that our design problem and its factors have changed. By doing so this has not allowed us to get the best understanding out of our matrix as we would have liked.	Once I have ID the stakeholder I try to research and look for things this single stakeholder need in order to use the project to its best function.	We each had a few of who our actual stakeholders where in this project but after talking it out and putting them in to the matrix there are many more than I imaged.	The matrix has allowed us to broad in our thinking and to get ideas we have not though of yet on how the ideas are related.
3	The matrix layouts the most important contraints and how they relate to other constraints but the group hasn't gained or lost any further understanding of the design problem because of the matrix.	There is one main stakeholder but each stakeholder will use the product the same way. Because of the overlap in needs there is a thorough understanding.	I do not think the our understanding of the stakeholders has been affected by the constraint matrix.	I do not see its use in any part of the design process ahead of us.
4	We are currently sure about what are we going to do. We need to come with several ideas.	We went to the police officer twice and we are very clear about how should we redesign the layout.	We will do our best in order to cope the impact that caused by the technology constraint. We can prototype the basic buttons layout by using foam or some other material.	Every product has constraints. We have a decent one. The only thing I am concerned about is we only asked about one police officer. He said he does not like the button and control of the radio system, but we are not sure about other police officer. Maybe they like the current layout instead of changing to other forms.
5	We haven't used it as much. We primary focused on the user contraints. And tried to create a physical object to meet those contraints	We haven't discussed them much	There are some stakeholder that does not benefit from our design, but they have little contact with our product, so they don't have much need for then. However the people they interact with do.	Haven't found it to be to useful during the actual prototype.
6	I noticed that the majority of the interactions occured in the usage part of the matrix. Therefore, we need to ensure we are weighing the majority of the decisions on that field.	We accounted for the patients and nurses well. However, we need to think about how adding holes in the pole will affect our manufacturing.	We need to re-evaluate the manufacturing stakeholder.	No real complaints about it. Just haven't sat down and anaylzed necessary changes yet.
7	The constraint matrix helped put things into a logical perspective. We now have an understanding of where we should put a greater amount of effort, and what we should focus less on to complete the project on time.	Our initial meeting with the nurse definitely gave us a better idea of the stakeholders in the project. However, we are yet to explore manufacturing, production, and the stakeholders that exist therein.	The constraint matrix has helped put into greater perspective the stakeholders involved, and their constraints in a general sense. What we haven't really delved into is the role of each of these stakeholders in specificity and where problems may arise with them.	It has helped us so far, and I truly think that as we continue our project, it can help us identify our constraints better in a more organized manner.

Continued

Table C.8: Qualitative response data for experimental survey 2 (part 2).

Table C.8 continued

8	I believe it can be very useful, but I honestly haven't given it enough thought yet. I will really need to sit down and look at it.	We have spoken to many people who are in our user group. We have a good understanding of what they need. We can always learn more though. Whenever we come up with a new idea we always want to go back and ask if this seems like a good idea for them. Since none of us have scuba dived before it could be difficult to completely understand what they need.	It has helped realize all of the various factors involved. For me, it has made me realize that money is a real issue. We ciould design a communication tool for scuba divers but the technology constraints and market constraints can really limit what we come up with.	I think it has potential, and I think we will definately turn to it soon for better decision making.
9	I has had a minimal impact, but that is perhaps due to the way we filled it out. We, for the most part, completely designed our first prototype and then filled out the matrix. We looked at our prototype and tried succinctly put the problems we designed for into the matrix.	I would say we have a very solid grasp of the stakeholders having thoroughly talked through it with the group. Again, we will have a better idea of that tomorrow after the first prototype presentation.	It seems we have leaned more towards designing for specific constraints, and then looking back to see if as many of the stakeholders needs are met as possible.	It hasn't seemed to help or hinder our project.
10	We have constructed a good, informative matrix but we still need to take time to review it and see how we can use it to benefit our design.	Our design idea lends itself to only three primary stakeholders. These being the dog, owner, and public. Since our design is a dog leash/collar it seem pretty obvious that these three parties are our stakeholders.	We have yet to apply our completed matrix to the designs stakeholders. We still need to take time and do this.	The completed constraint matrix seems like it can be beneficial if we take time to evaluate it and see how if can better our design
11	Right now, we have not completely nailed down what type of communication we will be doing so the matrix has not been utilized a lot.	We have a decent understanding from the 2 different dive shops we've talked to as well as the scuba club president. What is important is that we go back to those people and continue our discussions with their input in mind.	I feel that we, as a group, have identified the stakeholders already. This was done before we had the matrix.	I still feel that this will be a valuable tool as our process progresses.
12	It was very nice to be able to spell out our constraints and what we think as a group to be the weight, etc for each of them. However, it is also difficult since much of it now is still theoretical and it is hard to pinpoint how to overcome the constraints individually and on an interaction level.	We have mostly obtained a firefighter's or medic's point of view in this project so far. We have yet to observe or interview some obese persons that would test it as well.	It seems like each box in the matrix affects both at this point.	I think with more research it will be more useful but all of us are not very sure with some of the constraint attributes and/or interactions in how they will impact our project.
13	The constraint matrix has greatly helped us understand the correlating factors and constraints of our design so that we can more readily approach the design with all aspects in mind.	The shadowing of the stakeholders was a huge help in understanding their needs, but more exposure and getting them an actual prototype will be of greater value to watch how they use it and receive their feedback.	Similar to the previous questions, the constraint matrix has helped to gain an understanding of what correlates and the weighted value of what is most important in the design as compared to what is least important.	I approve of the matrix and think that it is set-up quite well. While it requires some useage to get the hang of it, the better you understand it, the greater value it is.
14	We filled it out after completing our mostly completing our current prototype so we haven't tried to use it to alter our design yet. It did sort of review the different traits of our design though, which helped.	Just thinking of the different people that come into contact with the iv poles besides the nurses helped figure out stakeholders.	We were already pretty aware of the stakeholders.	I think it's helpful but we could probably get by alright without it.
15	At this point, it has been helpful in describing what features we want, but we had that narrowed down before hand. Once we get into it more it may prove to be more useful.	Our person that we shadowed may not be our user. We are going to explore some other bike shops and also attempt to get some firsthand opinions from cyclists on Reddit.	We haven't gotten into this yet, in my opinion.	I feel like it has potential. But I also think it is incomplete due to my and my group's need to rethink our product.

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Table C.8 continued

16	The biggest thing that helped us was just sitting down and talking through everything. We all gained a better understanding by being forced to talk through the constraints.	We understand, but by gaining a good understanding we have found that it is near impossible to satisfy all user groups with one product.	I think we knew beforehand, we haven't really used the matrix yet to dig into the specific problems.	It's better than a final report.
17	Maybe after meeting with Paul today, the group would get a better understanding and interpretation of the matrix. At this point I can not answer this question.	There are not many stake holders (at least at this point is what we think), we think that the main stake holders are the users (handicap), rehab centers and manufacture. But maybe after meeting with Paul today he could give us feedback and proceed from there to get a better understanding.	At this point just a little. Probably after getting feedback from Paul, I could provide a more accuarate answer.	I think it is a useful tool, but is vague. Different individuals would have different numbers in their matix. But it is a great to considere changes and see what affects when making a dessicion in the design process. It helps to see what changes can be made before the manufacturing stage.
18	It lets us to directly see impacts of features and think through them.	We have talked to the user to see what their needs are.	Let's us consider who each part will affect	It took some time to fill out but overall not that bad
19	It is still fairly early for us to tell since our design is still in the beginning phases. But it has allowed us to think about the constraints and what we can do improve the design.	We were able to go to the plant and talk to the workers and management to see what they needed/wanted to help them with the job.	When coming up with constraints, we first had to decide which people might be impacted by the design and how they would be affected.	I guess it has benefits but I also think we could be making almost the same progress without it.
20	We generally felt that we didn't discover anything new from completing the matrix and do not feel that we will refer to it later.	Talking with police officers was the most helpful. We don't know much about horses though.	See above	I can see how this would be helpful for a more complex design scenario but for our situation, we didn't get a whole lot out of it.
21	It has shown us how interdependent so many of our constraints are.	We have a good broad understanding of the stakeholders but we don't have a good understanding of everyone that is involved with the tool. I think a conversation with some of the major users would help to identify some more stake holders and potentially obtain more needs from them.	I feel that the constraint matrix hasn't made much of a difference for us because the tool is for such a specific group of users.	It has been helpful but at time difficult to work with because of the software. Some better descriptions of all the columns and some more examples would have been helpful.
22	We have not utilized the matrix to any significant extent yet.	We know what they need. But the product just isn't a high priority, so we are designing something that no one will ever buy.	We have not utilized the matrix to any significant extent yet.	I hope to utilize it more and allow it to guide us to a breakthrough. We need to find that intangible something that is missing from making our design a good one.
23	We are still trying to understand it and utilize it to its fullest extent. Since is the first time any one of us has filled one out it is a new experience for us.	The interviews have helped tremendously. Getting to meet with them as a group can be challenging due to various schedules but when we do get together it is very helpful to ask questions of our user and obtain feedback. There's still much more we can learn from the firefighters but that can only happen by spending more time with them and trying to put ourselves in their shoes.	It's a more technical approach which can help with comparisons/relationships between constraints.	I'm hopeful that as we utilize it and understand it more that it will become more useful in our design process
24	Unfortunately we haven't worked that much on the matrix, but that is our goal during the weekend.	Since I personally am a user of the artifact, it is easy to understand one of the stakeholder's needs.	We haven't worked as closely as we would like on the matrix.	Since it shows the relation between the constraints and how they impact the stakeholders, I think it will be a tool that we will really take into consideration for the design and it will make it easier to find a way to make the design better.

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Table C.8 continued

25	Although we've made the constraint matrix, we haven't fooled around enough to get any useful feedback. Most of our criterion, we view as important, so it's hard to differentiate the factors.	The user and the manufacturer & assembly make sense, but depending on the scope, the stakeholder could care about every feature, except a couple obvious ones.	A little impact because it forces us to realize how many different kinds of people handle our product. In this class, without any manufacturing background or detailed design, it matters very little.	I'm neuteral. I could see the benefits, just not in this class. Furthermore, we haven't worked with it enough, and we don't deal with the benefits in our design.
26	We already knew most of the design interactions, and the interactions that were highlighted by the constraint matrix were ones of lesser value to us.	We have been able to talk out the shadowing to the one group member who was unable to go. We also have a rather simple list of stakeholders as well.	We already knew who was going to be effected by what constraint, and there were no interactions that were new to us.	It was busy work that gave us no added value to our project seeing that we had a simple design and most of our interactions were very inuative.
27	The biggest thing the matrix helped was seeing which constraint had the largest effect on our project and that is the one we focused on the most.	Sometimes I have questions that only the dentist would know and others we try to make an educated guess if the information is needed at that point in time.	Our stakeholder was already clearly defined.	Seems tedious (our group's experience was and sometimes we found ourselves laughing about how things related and how actually relevant the number we assigned was to the relationship) but does help with the major impacts of relationships between constraints
28	At this point in the project, the main advantage of the constraint matrix was forcing the group to write out all the constraints. For this particular user (firefighter) there are many unusual or unique constraints. Brainstorming solutions without having the constraints clearly identified and agreed upon by all group members proved to be almost impossible.	I feel like we have a good understanding of the stakeholder needs. The fire department has been very good about giving honest descriptions of their jobs and difficulties, which has helped us understand their priorities. Using / testing the equipment has given us a good understanding of what might work and what might not work. It has also helped us identify interfacing points and current physical constraints on the user (weight, limited vision, limited mobility, etc.). The only thing that would provide additional insight would be to shadow a firefighter on the job (during a call).	It is good to identify what constraints affect what stakeholders, but for the most part, this was already obvious without the need for the constraint matrix.	I think in this environment, with this particular group, the constraint matrix is a valuable tool that will help us get to good solutions faster.
29	It has has greatly helped in determining how the needs of various users conflict with one another and then focusing our design direction to best address the design problem. It helps frame the relevent factors to create a clear design problem.	Our groups project is heavily tied to users, the entire point of this design is to better adress the needs of all users rather tha making only one group very happy. We keep a very close eye on the user needs. Interviews with the users, observations, and the matrix have greatly helped understand the stakeholders.	The matrix has helped see how the various stakeholder interests conflict but has not really aided in determining what those needs are or who exactly the stakholders are. It's a useful tool but cannot be used as the only method to define and understand stakeholders.	I feel that it is a tool better used towards the begining of a design process when ideas are being condensed into more useable forms rather than trying to use the matrix while actual prototypes are being made. Still useful to have but not as much where we are at.
30	I think a lot of the information in the matrix is obvious, but it is nice to see all of it in one place and understand how changes to one constraint can affect others. The values are subjective though so that can alter the understanding of the constraints.	I think doing the shadowing is a great way to get an understanding of what the stakeholders need to accomplish. However, I would like to see a demonstration of how they achieve their task during the next shadow.	Again, I think a lot of it was obvious, but its good to see how all the stakeholders interests can conflict other constraints.	I think it's valuable to the overall work of the design.
31	We now understand the utility of the decision matrix, but we can't know more about what constraints there are, or how they interact until	Talking to firefighters and bouncing our ideas off of them has helped know more about their needs. We haven't discussed the needs of the obese patient as of	I don't think it has done much yet, but with more information and specifically asking the firefighters what they value most, the matrix could be more useful	I understand its utility more and it should be useful down the line.

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Table C.8 continued

	we've done a little more research on things	yet besides having the device work under the large amount of weight		
32	It has elucidated many interactions we had not yet considered. As we are a little further back in the design process our models are still a little too fluid to have felt real constraints, but I imagine it has saved a significant amount of future frustration.	We have had many difficulties getting access to different stakeholders. While we've had a good foundation, even our short interviews have revealed large unexplored areas and that some assumptions we made were irrelevant or wrong. We have corrected, but it is difficult with long feedback loops.	Most of the difficulty was originally coming up with the categories to input into the constraint matrix. By forcing us to consider those factors it has helped us be aware and track those issues. Though it has been helpful showing other interactions, the matrix has not yet done much more.	I'm a little concerned about how much reliance to put on it, given how it might direct things if we have an erroneous assessment when we first populate it and whether we will take the effort to review and correct it at times.
33	We just recently filled out the constraint matrix and have not had too much time to discuss it but just deciding on the constraints together has opened our minds up to many different ideas and helped us to see problems and relations we did not before.	We are designing a bike stand for a bicycler and the stakeholders were fairly tough to choose because we are mainly designing for one specific group with little interaction with others.	Our selection was limited in the first place so listing them here did not have much other impact. Though we might not have completed it correctly.	We are somewhat behind on our design process compared to others and we need to rethink our design a little bit so I think if we look over this matrix we recently filled out it should help us out a lot as said and I think this is a great tool to be using and it came at a great time too.
34	After determining our constraints, we have re-evaluated our ideas a bit and come up with new ones to cater to our constraints.	After creating the matrix, we have a better understanding of the stakeholders relevant to this project.	It has helped us a bit in understanding the stakeholders relevant to the project.	The constraint matrix is pretty neutral in my eyes.
35	We already know how our different constraints impact each other.	We know that it is important for children to not be able to use our product but still be relatively easy for adults to use and people to manufacture.	We felt like we already understood our stakeholders.	If I didn't have to do it I probably wouldn't have but it does help to keep track of how our constraints interact with each other.
36	The constraint matrix has helped a little. It showed some of the relations that we hadn't necessarily thought through completely for the project.	The police officers are crucial to this project. They will be using it day in and day out. Their safety will be in jepordy if the light is to fail during a raid.	The matrix helped the group some during in understanding the stakeholders relevant. It caused the group to think outside of just police officers, i.e. mothers at home.	We probably have not used the constraint matrix to its fullest potential.
37	It was helpful writing all the potential constraints. Also it was helpful to think about how one constraint might impact another.	The example matrix was very helpful to come up with stakeholders. An obvious stakeholder is the user, manufacturers and also the company/people that sell the device.	It is helpful because it also makes you think of the manufacture and seller, while the user would obviously always be thought of with or without the matrix.	Still kind of confusing but getting better by just playing around with it. Hopefully it will make more sense after lab tomorrow.
38	It helps us see all of the current constraints in one place and how it affects each other allowing us to focus on the most important aspects of the design.	We've put a good deal of thought into who could use this product and who is would affect.	Stakeholders weren't a huge focus at previous discussions, but using the constraint matrix has helped us to give due thought to this important aspect as well.	A useful tool for laying out constraints and prioritizing which are most important.
39	I has helped us focus on what factors we need to keep in mind when designing.	Speaking to police officers in person was a great boon to our understanding of their needs for this device.	The matrix has assisted in organizing which factors affect which stakeholders of the project.	It has primarily helped us as an organizational tool thus far.
40	The contraint matrix has not been helpful thus far.	I would say that thinking about who the stakeholder are has helped to understand them.	I don't think it has other than naming who the stakeholders are.	At this point, I do not see the constraint matrix as being particularly useful in this class.
41	It has made us think of some new issues but with this design has not really allowed use to utilize the matrix to its full potential.	We understand that the nurses and patients in the gown design will be greatly affected by this new gown style. understanding there roles and their influence on the design has allowed us to come up with creative ideas.	We understood who the main stakeholders would be but the matrix made us think of some new ones.	It is a great design tool but we have not be able to utilize it to its full potential. One idea is to give students a bigger design and have then fill out the matrix to really understand how some constraints effect each other.
42	We have only just populated the constraint matrix, so it's use has not yet affected our design process.	I understand the user and manufacturer part of the stakeholder, but I do not really understand the	Before the constraint matrix, I did not really consider the stakeholders other than the user.	It is pretty easy to fill out and gives a pretty clear idea about how the constraints interact.

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Table C.8 continued

		corporation portion. In your example, you use Nikon but our product does not have such an obvious corporation.		
43	Although our group pretty much knew where we wanted to go with our design process, the constraint matrix allowed us to think more in depth and work out a few problems in our individual designs.	I feel as though I do understand all of the stakeholders present in this project. The main thing to help with this understanding was the material provided by Dr. Lilly in lectures.	Although I believe that I knew the stakeholders already, the constraint matrix allowed us to outline this effectively and clear up any questions we had considering this.	The constraint matrix was somewhat lengthy, but really does provide helpful insight into what constraints impact others. For our project, the majority of the constraints were focused in the physical domain, so we did not see any major negative relationships in the matrix.
44	Honestly, I feel like we are trying to use it but in the end it seems more like a chore than a tool.	I think the example matrix made it very clear what stakeholders are but I think sometimes it could be hard to relate the term to a different product.	We knew our stakeholders from the beginning I guess it helped us a little bit with the interaction of the stakeholders.	Seems like a good idea and I think that its probably good to structure design criteria in someway but I think it is going to be very hit or miss with a lot of groups. As of now it has not helped a whole lot
45	It has sprung many discussions on how to go about the way we view what is most important and what is the least important.	I feel we have a great understanding on what the patients, hospitals and nurses need in order to make there lives more efficient.	it has impacted us in the sense of whats aspects of the design do we need to pay the most attention to, and what we can say that this is perfect and now we can move on to other aspects of our design.	I feel as though this will come in more handy after the next presentations because so far we have not had a whole lot of opinion on the matter besides paul and our group plus our contact.
46	The constraint matrix has helped to understand which factors are related in the design. There were some areas that were related that were not obviously related and we might not have thought about the relationship without the matrix.	The fact that we all use dumpsters and that they are relatively simple to manufacture has helped with our understanding.	The constraint matrix has helped to ensure that we thought about each stakeholder, but it has not made a huge difference.	It has been helpful.
47	The constraint matrix unfortunately did not significantly improve the group's understanding of the design problem. The relevant factors seen in the constraint matrix were already understood.	Our particular project involves very specific stakeholders and therefore, the group was able to target the stakeholders' needs through interviewing the potential users.	Our project involves a limited number of stakeholders and therfore, organizing the stakeholders in the constraint matrix did not reveal any new information and did not improve our understanding of the design problem.	While the constraint matrix offers a convenient method for organizing constraints, filling out the matrix did not reveal any constraint relationships which would steer the group towards or away from any of the particular designs being evaluated.
48	Not really worked on the constraint matrix.	will understand the stakeholders needs once we have our first prototype and take his feedback on that.	Not really worked on the constraint matrix. will do it this week.	Positive
49	A lot of what went into the constraint matrix we had talked about before.	Not being familiar with the process and the user was the greatest challenge in understanding the stakeholders	It has helped us to understand all of the different people we are designing for	It is helpful, but took time to fill out.
50	its nice to have the constraints laid out for us to make decisions but i feel as if we are all on the same page for what needs to get done and how that the matrix does not play a role in assisting what decisions or changes need to be made.	n/a	the EMTs have more focus on their needs	it has potential to be useful, haven't seen it yet though
51	It made us aware of some problems that we weren't really considering before.	Meeting with the nurses and asking questions helped a lot in understanding the various stakeholders and their concerns.	It helped us think specifically on who they are and what is important to them	It was a helpful exercise in listing as a group what was important and discussing the balance between some of these conflicting constraints.

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Table C.8 continued

52	It has shown us some areas that we can modify and improve upon.	We have a good understanding of what the operator needs are and how we need to keep our design simple to have it succeed.	We had a pretty clear understanding going into the design process.	Although it is a little difficult to do, I do believe that it has helped us come up with a better final design.
53	I think the jury's still out on the constraint matrix. Hopefully as we get further into the design process we will get a little more insight into the usefulness of the constraint matrix	Talking to our potential user during shadowing, and considering the problem from both the EMT and Patients perspective, as well as working as the manufacturer, has helped tremendously.	It gave a reason to think about the stakeholders, and made us consider who would be affected by this product.	I think that, moving forward, the constraint matrix can potentially be a very useful tool, but we have to learn how to really utilize it first.
54	It has focused us on what constraints we need to focus on and which ones we don't really need to focus on at the time.	Being able to shadow some of our users has contributed to helping me further understand the various stakeholders and their needs.	It has reinforced the fact that our group needs to focus on the end user for our project since they are they ones who are influenced by the most constraints.	It has forced me to think more about the design and the constraints on it when I might have looked over a few of them without it.
55	The main contribution of the constraint matrix is that it helps us to be always focused on what is really important in our design.	It was really easy for us because almost everyone we knew was a direct user of our product. Gathering information was easy.	The constraint matrix led us to think about all the different people that may have contact with the product. Both directly and indirectly.	I think it is a good design tool.
56	It has helped us in charaterizing our constraints and helped in realizing which set of constraints we need to concentrate more.	I feel the thing that has contributed in my understanding is that I am also a user of the product I am working on. It helps me understand what are the problems of stakeholders.	Impact matrix has helped us mainly in realizing our constraints and characterizing them.	It is really a great idea. Especially, for people with scattered ideas, it is going to be a lantern in the darkness.
57	No significant impact. Was filled out after designing the prototype.	We considered all users that came into contact with our product.	After looking at the example matrix filled out, we considered the manuf. and corp.	Not necessary. Takes a lot of time to fill it out. The benefits don't exceed the amount of effort to fill the matrix.
58	It helps us recognize what contrainsts relate to eachother so we can ultimately kill two birds with one stone when coming up with solutions	We all have used a new and old gas can before so as a direct user, we have a good idea of what the product is missing. However we are not involved with manufacturing these products so it will take a little outside thinking on our part to consider those stake holders as well	We are able to recognize the magnitude of the impact that each constraint deals with the each stake holder	Haven't seen a direct use for it yet but this could change as we run into more problems as we continue with our solution
59	It has been helpful in keeping us on track and giving us direction. serves as a guideline.	We understand from a user's point of view as we are all stakeholders as we use dumpsters.	we have come to understand that we are designing for all the people who will come into contact with our product.	my understanding of it keeps getting better and better.
60	At this point in the project our group really has not used the matrix all that much. The design problem we came up with was pretty well thought out and the different factors that went into it were also pretty well defined before the matrix was used.	With our product it can be applied to many different everyday people and this allows us to see it first hand all the time. However, it would be nice to see it used in more of an extreme situation which we are trying to design for as well.	The stakeholders in our design problem again were very well defined at the beginning of our problem so the matrix was more helpful in just reenforcing them.	It wasn't extremely helpful to our group but still got our constraints on paper and allowed us to look back on what we need to focus on.

Survey 3 Qualitative Responses (Experimental Population)

ID	Attitude about design project and final solution.	Attitude about quality of teamwork.	Shared understanding of the design problem, and ability to reach consensus.	Impact of CCMT on understanding of the design problem.
1	I think we did really well to address all of the concerns of the user, but I wish the prototype quality could be better since it is meant to be fully funcitonal.	At the beginning of the semester, I felt like I was doing most of the idea formulation and prototype assembly. But during the fabrication of our last prototype, I think my team really put in a lot of effort to help out, and they came up with some great ideas for design problems.	Our group did a great job of visiting the user in person, and observing how she uses her tools to accomplish tasks. So we had a great sense of her abilities and limitations.	We haven't used the constraint matrix in the idea formulation or the prototype fabrication.
2	I feel I gather a great deal of experience about design and learned so much from it. Some improvements I could make would be to slow down an try not to rush the prototyping step. Something I did well was I was able to understand the users needs very well.	The reason I rate it a 4 out of 5 was because I our design come out better than we all though put a lot of work into it and it really looked nice. Where we need some improvement was better team communication and a better acceptance of ideas.	A big hinder was as a group we could not convey our ideas well enough for the other member in the group to understand and they where very against changing initial ideas.	To me the matrix had a great deal of impacted by filling in the necessary categories the matrix became of great importance and understanding of how each and every essential piece was connected. To my group they didn't share my thoughts on the matter so the matrix was rarely used by them.
3	Our design had issues when it came to feasibility of production. The assembly of the design was also complicated, making it difficult to be put in production. However, I think our design addressed the current problems regarding the functionality of the current models.	Everybody worked very well as a team and produced quality work.	Some members of the group could relate more easily to the product because of experience using it in the past. This helped some of the members understanding to be better/higher than others.	The group did not feel the constraint matrix helped our understanding of the design problems or contributed to the completion of the project.
4	Our product can be improved by asking the users attitudes toward the product since the communication is very valuable.	Every body works coherently.	We have group meeting regularly so we share our ideas very often. The product is not from one person's idea. It is from the combination of four.	Since our constraints are not big factors and our product concepts are very straight forward.
5	I feel that our product exceeded our initial expectation. We took into consideration of all of our design constraints and addressed our most important ones.	I feel that not all members of the team contributed equal amount of work. Althought every did contribute some.	I feel that understanding which one of our constraints were the most important greatly improved our productivity. The part in which I felt we took the most time with was deciding how to adress these constraints without completely disregarding another constraints	Although the excel file matrix wasn't used much we did compare our constraints and weighted then against each other during our discussion and brainstorming. The medium of it wasn't good for use, we liked writing it out on the dry eraser table and circling and staring things better.
6	I think that we solved three a huge problem for the nurses. The first was consolidating the mess of cables from the IV pumps. The second was making it easier to connect the heavy IV pumps to the pole. The third was reducing the need for an extra nurse to move a patient from room to room.	I had a random group, but we connected well and efficiently solved the problems at hand.	As previously mentioned, my team worked well together and talked through problems if there wasn't an initial complete consensus.	I believe that we made many decisions for our project before the constraint matrix was introduced to us. I think the matrix would have had a bigger impact if it was introduced earlier in the semester. Maybe consider doing this in future semesters?
7	What we did well: addressing (directly) what we decided were the problems to begin with. Sure we did not come up with a super-patentable idea, but I believe that the simple modifications we made to the IV pole would be greatly beneficial in an ICU setting. What we could	Group work went well. We were all responsible, and there was an even contribution from all. Roles became clearer as we progressed through the project.	Discussions certainly helped. One of our groupmates was more artistic-minded, and almost everytime he had an idea, he drew it out. That gave everybody a better understanding of the problems at hand and how to address and visulize different solutions.	Constraints identifcation was key. I really liked the fact that our project was focused to a certain number of problems, and our constraint matrix reflected just that.

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Table C.9: Qualitative response data for experimental survey 3 (part 1).

Table C.9 continued

	improve upon: A more polished prototype. Testing our prototype in various situations (checking fits and everything.).			
8	I rated it as a 3 because I still feel there is a lot to be done with the design. The main concerns I have are with the technology. We did find some technology that could be useful for our design for the Scubuzz, but it would be hard to make it inexpensive, and this is one of our major constraints.	I thought the quality of our teams work was pretty good. We all worked hard, gave out pretty good ideas and worked together pretty well. there was one team member that really didn't do much and it got pretty frustrating at times.	Well, we were able to come up with good ideas and converge on ideas. I think the fact that most of the team was pretty open minded that we were able to work pretty well together.	The design constraint matrix worked pretty well but unfortunately we didn't expect technology to hinder our design process so much. We believe that our design could potentially work but the technology may be difficult.
9	I would consider it a 4, or, good. I think the call button attachment to the gown could be greatly improved, along with its size and general look. Additionally, the means of closing the gown could be improved. I think the rest of the improvements were good (mesh pocket, movement assistance loops, catheter bag). I like the general concepts we developed for the closure and call button, they just need a little refinement.	The group really came together the last couple of weeks. Initially I think peoples ideas were rather far apart and the collaboration was not the best. As we talked through things, made compromises, continued to refine the design, and learned each other's preferences I think we worked well together and created a good product.	The biggest hinderance was the shadowing. Only one person (myself) was able to go to the shadowing as it was in my hometown near Cleveland. I communicated what I saw as best I could, but I think some of the problems were still not fully understood by each member.	We tried to address as many problems as possible with the hospital gown which made it a unique challenge. There weren't as many problems wrong with the gown itself as we were trying to use the gown as a vehicle for change in other areas of the hospital. I think we did a good job of tackling as many problems as we could with it. As it turned out, entirely by chance I believe, not many of our constraints/features interacted with each other. Because of this the matrix didn't tell us or help us much.
10	Our design looked good but its functionality could have been more accurate and improved upon.	We all worked together well and everyone was willing to do their fair share	We all were working towards the final goal of completing a great prototype. One thing that hindered or ability to reach a consensus was a lack of time to further improve design	It showed us what factors were most important and how they interconnected to the other constraints
11	I felt like we took a very close look at all of our design constraints and addressed them properly, however, we needed more time to figure out the finer details such as the actual technology that should be implemented and how that effects cost.	I felt that everyone in my group put forth quality work except for John Harman. He was frequently late or missing from meetings and never seemed to want to go with the flow of the rest of the group.	The only reason that I'm not giving this a 5 is because I'm not sure that John fully understood where the other three of us felt we should go.	Honestly, the constraint matrix helped at the beginning when we were trying to organize all of our ideas and sort them out, however, moving along with the design and towards the end of the project, we never looked back at it.
12	This design was rated a 4 since we were not able to fully test an obese person due to the materials and we had to borrow the stairclimbing feature instead of prototyping it.	We worked as a team as productive as we could. We held each other accountable for our parts and made sure everyone was on the same page. We also divided the work up as evenly as possible as well as all the costs.	I think our diverse background and ability to be truly open to others' opinions during the design process as well as our mission to succeed in this project contributed the most to our group's shared understanding and ability to reach consensus.	The matrix impacted our group's understanding of the project by helping us examine some of the possible routes we could explore in ideation, narrowing down our scope in what matters most to our stakeholder firefighters, and what could be feasible with our allotted project time.
13	I feel that our design process was very productive and seemed to closely follow the ideal design process that it used in practice. In terms of improvement, I think I could have more effectively used the constraint matrix and user interviews.	I thought our group worked very well together but was not the most effective. I think that our gruop meetings were not productive since the other teammate seemed to prefer to rush the process and get out of the meeting than do a good job on the project.	I think the labs that we participated in were well organized and the feedback provided by Paul was helpful and effective in moving forward with the design process. The user interviews were also incredibly helpful and invaluable to the design.	I think that we did not fully utilize the constraint matrix, since most of the numbers that we input to the system were rough estimations and didn't provide very objective values. This contributed to the overall reluctance to use the matrix since the usage of it was also mildly unclear.
14	I think it was good but could have used some finishing touches. If we could have demonstrated our idea for the clamping system and coupler better it would have made our prototype more presentable.	I feel like our group communicated well and did and everyone did a fairly even amount of work.	I think the most important thing to understanding the problem was our user shadowing, but I think we would have understood and agreed more if we were able to go back later and spend more time with the user. I	We were basically aware of all the constraints on the constraint matrix before we used it but hadn't systematically thought about how they were connected. We hadn't put much thought into shareholders though. Using

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Table C.9 continued

			think it also would have helped if we had all been able to meet at once when we were building our prototype.	the matrix showed us what features should be most important in our design.
15	For the time we had to actually push our idea, I'm extremely happy. Not quite a 5 because I feel there is still a lot of ground we left uncovered... Given more time and maybe having our idea a little earlier would have been a substantial help to our "final" design.	From the very beginning, I had a good feeling about our group. We were always on time to project meetings and benefited from each others' strengths. Some of us had the broad, crazy design thinking, others were more inside the box thinkers. The combination worked out great for us.	I feel like none of us have the full understanding of our design problem, simply because we aren't cyclists. We would probably not use this product in our everyday lives, so it's hard to wrap our minds around the problem fully.	I think that when designing and deciding, we referred to the constraint matrix. It's a good visual tool to see interactions. In the future, if we were to make changes to the product, I feel like this tool could be very helpful.
16	I was really excited about this project at first, but then it kinda just trailed off as we realized this was an assignment for a grade rather than a real world problem. The reason I say that is that we forced some of the process because of deadlines.	It wasn't too bad and eventually work got done but I felt like I was pulling teeth at times.	Well first off, I feel bad for Wuyang, his english skills just did not allow him to understand us that much. And everyone else was going onwithout him because we had to.	Ehhh, we used it a little bit. Mostly it was just another assignment on top of all the oher one's in the quarter that was completed as part of a routine.
17				
18	I thought overall the design went well especially in cutting out the fat of the design. But it is not ready for manufacturing.	Overall I feel we worked well together.	I think we came from very different backgrounds so it was hard initially to established the main goals but I believe we worked that to refine the design.	It helped us put into view the overall relationships and how one feature can effect the others.
19	I thought the final design prototype turned out better than i expected. We probably could have improved the mechanics for the prototype, but we did pretty well I think for the time we had available for the project.	If anyone in the group lacked contributions, it was me. But we managed to find meeting times when we needed to. In order to level out input from each teammate, I think we could have mapped out the next steps a little better and distributed them accordingly.	We held meetings regularly or at least when necessary and everyone contributed to the actual design thought process.	I think the matrix clearly identified the constraints but didn't really influence us to thoroughly evaluate them. I think given more time and working with an actual implementation design it would have been more useful.
20	I thought the solution we reached was feasible and was communicated well by our final prototype.	Great experience, would work with these gentlemen again.	We communicated honestly and made conscious efforts to see all perspectives.	We completed the matrix and that process had some benefits but we never referred to again after that.
21	I feel that our design still needed improvement. It wasn't until very late that we discovered the true constraints.	Some people pulled more than their own weight.	We met with two different dental students and when we met there was never a time where everyone was attending the meeting except for myself. This left my trying to express to the group what the dentists thoughts were. This could have been solved if everyone would have been able to attend the meetings with the individual dentists.	Once we knew exactly what the most important constraints were to the dentists we could see how the related with the other constraints. This helped to weight some of the decisions with the actuation system and the design of the air delivery system.
22	Our design was reasonable considering the object we chose. However, we chose a poor object to redesign.	Three of our members contributed adequately. One member had nothing useful to contribute really. The member just blindly did a few tasks just because he was instructed/requested to do so.	We have talked about our design a lot, created a constraint matrix, talked to the user, built a prototype. After all this we have a pretty good idea of the problem and how well our product acts as a solution.	It helped somewhat. But our design problem was pretty obvious.
23	One area of improvement would be in loading bariatric patients onto our transportation device. Also, we changed the scope to not include stair-climbing but after visiting our firefighters they requested for the feature to be included. This is an area that could be developed further. However, given the time frame, we	Out of all the team members, I definitely put the most time into making the prototype- probably close to 3 times as many hours- 32 vs 10. It didn't seem like my team members had very much experience in the shop. They didn't seem comfortable using the power tools and when they did drill some holes or make cuts they were	We were pretty much in agreement to the plans for our concept, however, when it came time to make the final prototype there was disagreement. They didn't want to add the 3rd and 4th swing-out support legs (with casters) or find a way to stow the leverage tubes. I felt it was necessary to address those as they are inherent to	We were really focused on coming up with a final solution within the time frame. The matrix was not really a prominent tool that we utilized to help us with that. I think we viewed it as more of something that we needed to fill out after everything was finished. This is definitely not how to get the full potential out of the

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Table C.9 continued

	were able to develop a prototype that demonstrated the concept to cover the defined scope at the time which was to aid in transporting bariatric patients in non-fire emergency situations. The prototype was able to carry the load of a non-bariatric person and demonstrate how it was intended to be used. As a communication tool, it succeeded.	not straight or aligned very well- not so good craftsmanship. So I ended up doing most of the work. They also said they needed to do work for their other classes like capstone and didn't stick around for very long in the shop. I believe it was a combination of not having enough time due to their other class commitments and not being comfortable in the shop that attributed to the lack of teamwork on the final prototype. Thankfully, they helped out more with the powerpoint presentation, matrix and report writing.	the way the device is used and transported. Without those, we would not have been able to effectively demonstrate our concept. Again, I believe this was because they were feeling pressure from their other classes to not spend any more time on the prototype as opposed to them not thinking the features were important.	matrix tool. We could have tried to use the matrix more as a planning/decision making tool but we didn't- for us it was more of a post evaluation tool because the majority of our efforts were focused on creating the final prototype and presentation.
24	We consider as many constraints as possible, as well as the stakeholders. I think we really worked as a good team. We were not at our best creating our prototype. More knowledge about prototyping could have been important.	Everyone was interested, at the end, to deliver the best prototype possible. All of us were eager to give our best in each step, giving our time for the project.	Definitely the labs were the best way to achieve consensus. Every time we had a lab, we will talk thoroughly about the project, the options, what is going on, and discussing it with the TA.	At the beginning the matrix was very useful, we got a real understanding on how each constraint was connected with the others. Later in the process we didn't pay more attention to it, maybe the matrix's goal was already achieved.
25	User feedback had by far the most impact on our design. If the designs could actually be used and built by our team, the details would have been taken more seriously. Overall, the wealth of ideas and teamwork made for a well thought out product.	Again, motivation would have been improved if we could actually build and use these products. Otherwise, our team worked fine together.	Some stubbornness got in the way. The main hindrance to our groups full understanding is the commitment to thinking about the entire design-through manufacturing process. Because very little of our project had to do with manufacturing, it wasn't considered.	With more at stake, a constraint matrix may have been helpful. However, without making the product in depth, there wasn't much motivation to fully utilize the matrix.
26	Our design did not solve any of the major problems we outlined.	We were all on the same page for when work was needed to be done and how much effort was needed in this process.	We all had shared experiences with issues that our product were trying to adress.	Most/all constraints and interactions were already known.
27	I thought it performed the way we wanted. And looks similar to what we wanted.	Everybody has there strong points and they were utilized.	We all understand the process.	It was good when we first made it. But we never looked at it again until we needed to write our paper and make our presentation.
28	The final product was praised by the firefighters as a great idea that would be a big help. The prototype was tested and proved to significantly ease the transportation of a person on level ground. However, there were still many aspects of the problem left unsolved at the end of the project. The design of the dolly still did not ease getting the person onto the backboard, and the method of sliding the board into the dolly was not reasonable. These are issues that would need to be addressed if the design were to continue in development.	Everyone on the team was a hard worker and was dedicated to making a great final product. However, there was a lot of conflict over what was reasonable to accomplish in the allotted project time, and the team had difficulty agreeing on a manageable scope.	The team benefited from insight from the firefighters, who were able to clearly communicate what they wanted to do, and why they couldn't do it with their current equipment. One hindrance that the team had was a desire to focus on prototype quality over design quality. There was a distinct shift away from what features and functions would best solve the problem towards what features and functions would make the best prototype. The end result was a good solution, but it did not properly address all of the issues that the team had set out to address.	The team had a good understanding of all constraints, even though the final design did not fully address all constraints. With additional development time, the design could have evolved to better address all constraints. Since there were many constraints for this project, the constraint matrix helped in listing them so the team would not forget about any them. A usability note: we weren't exactly sure how to phrase the constraints so that we could best assign numbers to the correlation.
29	I feel that the final product was very well put together. It meet our design solution needs without becoming a product that already existed. Our creation meets the specific needs of our problem	The team meshed very well despite having difficulty meeting together. Assignments were completed effectively and efficiently by the individuals they were assigned to. Group review	The matrix proved useful in ensuring that all members understood what the most important factors as we all assessed and quantified the value of each category.	The matrix was very useful in determining the key areas of focus. It allowed us to focus on the key aspects and helped create a product different than what already existed.

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Table C.9 continued

	very well. The design needed testing to ensure that it could fit all that it was supposed to and see user reaction and feedback.	and alterations to the deliverable's was very constructive.		
30	I've gained a lot of excitement about the design process and seeing a idea in my mind be molded and transformed into an actual product.	I think we did a good job of taking everyone's input and integrating it into our design if it worked.	I think the shadowing did the most for our group reaching a shared understanding because none of us knew too much about medical stretchers before and the problems associated with them. So, with the shadowing, we all were exposed to the same problems.	I think it did a good job of having us think through all the possible constraints on our design. However, I think our design would need extensive testing and more constraints could come out of that.
31	I think our design was good considering the planning that we put into it. We didn't finalize a concept until the week before, and didn't start putting it together until the saturday before the due date. I wish we would have narrowed our scope earlier in the process so we could have really worked at how to solve a simpler problem, rather than our efforts to make a 'superman' product that would work for everything...	We all worked hard together, but some of us had different expectations for our project than others which made it difficult. It also was hard having someone with professional design experience because a lot of times they automatically assumed that their solution for a problem was the best.	A lot of what hindered our ability to reach a consensus was different people wanting to make products that did everything rather than making something that was feasible for us to do.	I think there is some impact in the fact that it caused us to think about how different constraints interact with each other
32	While I really like the design and the ideas it conveyed, I wish it could have been further along in the design process. I feel like there are many potential pitfalls and problems that would not be apparent until the entire package began to be implemented.	Everyone worked well together and generally accomplished the goals we set. Everyone pitched in equally and distributed work fairly. Though there were times where members missed meetings or did not fully complete a given task it was understandable, and we were all equally culpable of it at some point.	Lots of communication, a willingness to compromise, and a desire to incorporate only the very best ideas, wherever they might come from.	While it directed things more at the beginning when we first formulated the design matrix we did not reference it much thereafter. It clarified the problem and brought some issues into sharp relief, but afterwards we did not utilize it as much as we perhaps should have. Since we didn't consult it much, we also never realized that we could update and modify the matrix.
33	I felt like our final design was very well put together and was an intuitive design as well that solved the unique problem we faced well. My group struggled a lot at the beginning of our design process and we never had anyone to truely shadow as our visit to the bike shop provided us with little results, and thus our final design was not worked on much until the last few weeks of the process, and I believe that if we had worked on this design more than we did it would have come out better. I still feel though that our final design was very well done.	We were all very busy with work and classes this semester but my group was very well organized and communicated very efficiently and we were able to get through a fairly difficult problem with pretty big time constraints as well.	I would say that the only only thing that hindered our shared understanding of the product was that we did not have a true person to dedicate our design problem to so we ended up basing our problem off of a group of people or possibly individual people we knew so that we were all not collaborated on this situation. I still believe that we had a great deal of shared understanding throughout the design process despite this.	We took quite a bit of time to go through the constraint matrix and specifically fill out all we could and take the time to think about how each constraint applies to which to see how each change affects which. We ended up filling out a matrix twice because our design changed considerably and filling out the matrix the first time helped us to understand that we needed to change our design around a lot.
34	I think our design was really good and would help the hospitals out in many ways. The closure system could be thought out a bit more. I think the call button was really good and was done very well.	My group had great teamwork. We worked through the design process in a good manner and came up with a solution to our problems.	I think we all understood the design problem we were facing and worked well as a team in understanding each others ideas. This helped us to agree on a good design.	I think the constraint matrix helped out a good amount. It helped us come up with all of our constraints to help us determine a design from them.
35	We could've spent more time figuring out a way to make the gas can work properly.	Everyone showed up to all the meetings and helped work on the product.	We often got hung up on our own ideas instead of searching for new solutinos to the problems presented.	We didn't feel the constraint matrix helped us solve our problems.

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Table C.9 continued

36	I feel like the group came to a practical and simple design. I can honestly say that we put a lot of thought into our design to come up with a solution that police officers could use every day. We have a couple of areas where we think we have the design figured out but were not able to prototype it. This areas could cause issues for potentially taking the product to production. As mentioned before, our design is very simple and practical for every day use.	I think the group evenly split up the work among the group members. Everyone pulled their weight without having to be motivated by the other team members.	During the design process, the group all spoke with police officers. This really helped the group dig into the problem of what police officers really wanted in their design. We also met on many occasions to talk about the design of the puck lights, housing, and release method. Further, we also discussed many ideas and the feasibility of these ideas before coming to our final design solution.	After initially completing the design matrix, we rarely referred back to the constraint matrix. However when we did it was very useful.
37	I think my group successfully created a device that did everything we wanted it to do. The main goal of our design was to help a specific user, Linda. I think we were greatly successful in this, we created her a device that she loves and that she will use everyday, which was our main goal.	I had great team members. We were able to come up with a weekly meeting time, which was helpful when scheduling other meeting times. We were also able to split up the work as evenly as possible and I enjoyed and got along well with my teammates.	Although there was some different ideas in the beginning of the process towards the end we all had a shared understanding. I think one reason for this was that we had one specific user and we all wanted a device that would be the most helpful to her. Having one user was nice because if there was any conflict we would ask Linda what she wanted or thought.	I'm sure we did not come up with all the factors and constraints for our project. We came up with many but I am sure there are some that we overlooked. The matrix kind of helped with design problems and the factors, but problems and possible factors were mostly pointed out by Linda or when we tried to use the prototype.
38	I feel like we did a relatively good job coming up with a solution for the context and constraints associated with our product.	We worked well together. Could have been improved by meeting together more often.	The constraint matrix we created for our product gave a clear cut visual representation of what we agreed were the most important aspects to our design. This allowed us to all be on the same page and move forward together.	Very useful tool for understanding how different constraints affected one another. Helped focus efforts on most important design parameters.
39	I think given the amount of time we had to work with and the materials we had available to us (ie a low budget) we created a design that accurately met the goals that we set out for it to meet. The real test we had for ourselves was whether or not the police officers would use the device, and many of them said that they would. Given more time etc I would have liked to have taken it further, but I am satisfied with what we arrived at.	Our team worked together very well, nothing to complain about.	We reached a shared consensus on many matters due to the input of the officers we were working with; many of them just told us flat out what they wanted in a device and we worked together to deliver on that as best as we could.	The design matrix helped us organize all of the information we had in an easy to read format. However, given the nature of the design matrix we could only fill it up with factors that we already knew about and rate interactions that we already knew of.
40	We put a great deal of thought and effort into the project. We worked with multiple users and used the skills we learned in class to create a product that best accomplished the tasks that the user was unable to do previously.	I thought the group worked together well. Although there were times we did not all see eye to eye, these disagreements pushed our prototype to a higher level.	Visiting and meeting with multiple users in multiple scenarios has certainly helped our groups understanding of the topic as well as our ability to reach consensus.	The constraint matrix was generally helpful. It did force us to think about how different aspects of the product related to each other, but we certainly did not hang the matrix on a wall to reference it throughout the project.
41	I believe that my group addressed a problem that has not yet been addressed and that we came up with a great design. The design contained features that were thoughtout and alln the features served multiple purposes. I feel that we could have worked on the call buttton a little more and maybe have thought about the locations on the loops and where they might be best	My group worked together well and everyone added one feature or another to the gown. We thought through each feature and did multiple iterations on the gown to come up with the best solutions to the problem.	The ability of two of the memebers actually being patients in the hospital for an extended period of time and the ability of the group to talk the group member who had direct contact with the user. This group member took great pictures and explained what was the problem in detail so that we coul all understand it. The reason why not full understanding is	It made us think about some contraints that we did not think about at first. This made the group go back and create new features to over come these contraints.

Continued

Table C.9 continued

	placed. The internal pocket as well as the idea of the call button where some great features that could be used in hospitals today.		due to the whole group not actually visiting and talking to the user.	
42	I felt we came up with a solution that was simple to use but provided functionality to the user. I felt our prototype could have been improved and we could have done more research to back up the technology part of the solution.	Two members of the group and I got along very well, showed up to nearly every meeting, and did our best to stay on task and get the work done. One member showed up about half the time and really tried to force his ideas on the group. He was difficult at times to work with and unreliable in general.	One member did not show up all the time. This made it difficult for the other members when he would show up and bring up things we had discussed in previous meetings.	If we had unlimited resources, perhaps we could have gone scuba diving and maybe we would have found constraints we were not aware of from just talking to people about the problem. The constraint matrix gave us a visual of the constraints we had thought about but didn't really verbalize. It also allowed us to easily visualize the relationships between the constraints.
43	I feel as though the persona chosen for our design resulted in many more constraints than originally predicted. Legacy issues were a big concern with our product, but I believe the design we conducted would in fact be used by the persona. Our manufacturing and design worked especially well, but both of these would have to be fine tuned in the future.	Meetings were a problem sometimes due to conflicting schedules, but the quality of work produced by the group as a whole was good.	One of the group members seemed to be a little more hard-nosed in terms of making decisions, but this did not turn out to be a problem overall.	Due to the many constraints, it was pretty apparent at the beginning what design we needed to implement. Nontheless, the constraint matrix confirmed those initial beliefs.
44	I don't think we really had a revolutionary idea. Nothing really jumps out to make you say that is really cool or intuitive. I think we could have worked a little more with our user and definitely spent a little more time brainstorming. Towards the end we more or less ran into the "get it done" mentality and that really isn't conducive to creative ideas.	We worked well together. There were struggles at times when there were conflicting ideas but they were mostly resolved. One group member did tend to be stubborn with his ideas but towards the end he became much more flexible	I think we needed to work more with our users. Also, when we did our shadowing we should've taken more notes and pictures. I think we still left creating ideas that we thought would be good not really considering to user.	Just filling it out made breaking down the situation and constrains a little easier but we didn't really reference it afterwords. It wasn't really stressed so it was more just an afterthought. Perhaps using it would've made our design better.
45	I feel as though the design process aloud us to think about each redesign and come up with the best solution. What i didnt like is that, almost every idea was shot down and we ended up doing whatever paul wanted us to do. Improvement would be more individualized thinking.	I like our team due to the fact that we all came up with different ideas and were not afraid to meet up when need be.	I beleive the fact that a few members in our group were in the situation where we had some user interaction with the current design, allowed us to reach a group consensus. We were to share our experiences, and be able to show more of the user point of view even though we did not have access to the users.(users=patients)	The contraint matrix allowed us to think of one redesign at a time. This allowed us to come up with the best possible redesign considering all the users and constraints effected by this. This also pointed our focus to the most important points of our design.
46	I was happy with the final design but I did not quite feel like it got there. There seemed to be an extra step that we did not quite take.	Everyone was flexible with meeting times and attended group meetings.	What contributed to the final design being a consensus was everyone listening to and considering alternate suggestions.	The constraint matrix helped to identify design tradeoffs. But if more time could have been spent with using the matrix it could have been more beneficial.
47	The design problem was tackled well in that we spoke with users in our product field and identified areas for improvement. We went through design iterations and got feedback from users. We then came up with a final design and built a working prototype. We could have improved on our assessment of other uses for our product and the way it could be integrated into the current setups (current dentist chair package purchases).	We completed a lot of work individually and then met to put our ideas together.	What has hindered our group was the fact that on different occasions, not all of the group members were able to be present for consulting the users/experts. What helped our shared understanding was the use of sketches and CAD models to communicate design ideas.	It seems that, because of our relatively simple product (mirror) and our narrow user pool (dentists), the constraint matrix did not bring to light and constraints or constraint relationships that the group had missed.

Continued

Table C.9 continued

48	final prototype had much better functionality than the previous one.	Brainstorming in improvising the final prototype was done pretty well by all team members	good understanding of user needs and issues with the existing product with in the team members. Rapid prototyping and playing around with ideas helped reach a consensus	degree of correlation of each constraint with the other helped understand the problem better.
49	We did a good job of looking at all of our possible options and coming up with a lot of ideas. Once we decided on the general concept we had a hard time figuring out all of the details	We did a good job getting everything done, but we split up all the work. I would have liked to spend more time working together, to make sure we were always on the same page.	To completely understand the problem, we should have gotten in touch with our user again to make sure they felt that we understood the problem.	When making the constraint matrix it helped us to think of all the different factors, but we didn't use it after we made it.
50	i had a positive learning experience. our solution addresses the issue at hand. a 4th group member would have been nice the learning experience of the design process was great, from beginning to end	we all worked well together. bob was extremely accessible and productive especially working around Jordan's and my schedule.	i believe we had a solid start to a great future solution to our design problem that the EMTs would like there were a few conversations or disagreements on what was essential for the final prototype. each person voiced their reasoning and we would come to a compromise	it gave us an initial starting point of what we need to consider, didn't use it much past that
51	There were a lot of good features that I think would work well in a final product. Our product wasn't all the way there however mainly because we chose a very difficult/complex problem to solve. Due to the complexity I think it would require more than a semester of work to really fully tackle the problem.	Everyone contributed and everyone had "specialties" that they were better than the other group members at. Everyone showed up.	Differing opinions on technology feasibility. We had healthy disagreements not bitter ones.	Our problem was very complex and probably had more constraints than we listed in the Matrix. The matrix was helpful in initially deciding what was and wasn't important but we sort of abandoned it and stopped updating it as our solution evolved. It was helpful but we didn't fully utilize it.
52	I feel like our design included all of the ideas that we wanted to include in the product. However, the final prototype was not constructed as well as I would like due to budget constraints. Also, I would have like to be able to develop the automatic brake a little bit more thoroughly.	It was difficult, at times, to get everyone to meet and contribute equally.	Some of us had a more clear understanding of how some mechanisms worked. Therefore, these people were put in charge of completing this specific task and the others did not learn about the mechanisms. If they had learned about it they may have came up with a better solution.	It allowed us to see where the important areas are in our design and we were able to focus more closely on those.
53	The overall design did a good job of solving the problems we identified, but our prototype left a little to be desired. We also could have spent more time on how the bed loaded into the frame and how everything locked in place.	I felt like my team was willing to help with any part of the design process or with manufacturing the prototype, but our different schedules left us with very little time to work as a complete group.	Scheduling conflicts meant that only two members of the group could shadow our user, which was less than ideal for having everyone fully understand the problem.	The constraint matrix seemed a little unnecessary at the beginning of the project, but as we got deeper into details I feel like the constraint matrix was much more useful.
54	I am very happy about the result of the design process. I believe that the process that we went through set us up for success. If more time would be put into the design to improve upon manufacturing and price cuts, then I believe that we would have a very successful product.	Our team was able to work together well. We were able to agree quickly and responsibly on ideas on how to improve upon our design.	I believe that we all had an even understanding on the design problem. The decision matrix was a good tool that helped us understand the important constraints on the product.	The constraint matrix allowed our group to further understand the constraints that we needed to focus on and how they apply to our design.
55	I think with found a good solution with our design. Unfortunately because of the type of product with did not have the opportunity to prove it in the real world.	All the teams member were committed with the project. It was a great team.	I think we did a good job identifying the design opportunities a narrowing the solution to the important ones. The it was easy too to reach consensus on the solution.	The matrix was very useful to help us focus on the really important constraints and design opportunities.

Continued

Table C.9 continued

56	I rated it so because I feel it is a good and a very useful design that is simple and at the same time usable, but there is still a lot of scope to improve it. It can be improved in the sense of adding other features like a lock , etc. Other thing that can be improved is how the stand gets attached to the sign post. I feel like our design is good but it can definitely be made great by giving time to think more about constraints and uses, and then coming up with a more useful design that can be used by any and every cyclist.	I think we are great as a team. All of us understand each other's ideas and work as a team to come up with the best idea and design.	Lack of time has sometimes hindered our group's shared understanding. If there would have been some more time in our hands, we could have come up with better design as compared to what we have right now. Our understanding of the most important constraints has definitely contributed to our group's shared understanding and the ability to reach consensus.	Constraint matrix, in a way, gave us the opportunity to know our constraints in the best possible way. It gave us a better understanding about our constraints and what we can do to deal with them.
57	Could have refined the end product much more.	Could have refined the end product more.	Just an overall understanding of the problem lead to a feasible, logical solution to which everyone agreed.	Kept in mind the manufacturer.
58	I see the design as a great alternative to current gas can designs today and has potential to help out a lot of users. The biggest problems to address is the sealing and the venting system. I think the 2 step opening instead of the 1 step opening is a good direction	Overall we worked well together and always found a time to meet. Everyone was accountable to show up and get work done.	Our meeting with the user really helped everyone understand the product and the problems with the current designs	It was good to see the all the constraints listed out and easy to see which constraints impacted the other
59	I feel that the top lids could be improved to make it more flexible.	Everyone put in their bests and goals were met at a timely manner.	The unanimous views on the most important challenges in using dumpsters. Everyone agreed on what problems to address.	The matrix helped us understand better what constraints were important, and how changing them would affect the rest of the design. It helped keep us on track with the issues we were trying to solve.
60	I felt it was a really great idea but would've liked to spend more time on building a working prototype of the idea	Everyone got together when asked to and finished what was needed	There were times when our group forgot what the main idea of our design was and were worried more about specific functions rather then the main features	Matrix was just a little to complicated to understand

ID	Impact of CCMT on understanding of relevant stakeholders, and stakeholder needs.	Impact of CCMT on ideation and solutions.	Attitude toward CCMT.	Likelihood of CCMT reuse.
1	Our matrix helped to identify stakeholders that would be involved if our product was produced commercially, but this did not significantly effect our final design.	See above answers.	Helpful in some situations, but it wasn't enormously useful to us.	Industry maybe. Some project that is more complex that what we did in class.
2	Again to our group it had very little impact. Even to me this part had less of an impact because this is the part of the process in which I was already very good at identifying and relating to the stakeholder's.	After review the answers in the matrix my whole initial design changed I rethought about how if I can't change say safety anymore, but I could change another part of the design that would directly correlate with safety .	It is a great tool and I see the great use in it but can be sometimes tricky to figure out the best categories to fill in.	It was extremely useful and I would use it again but I would first want to practice with it on smaller projects because as I said before it is fairly tricky to fill in the essentials. But I would have a very likely chance of using it agian.
3	I believe the group understood who the stakeholders were but this was not due to the constraint matrix. I do not think the matrix had any relevance in this area of the project.	When brainstorming ideas I did not reference the constraint matrix, therefore I do not feel it impacted our ideas.	Filling out the constraint matrix was not a negative experience but it did not seem beneficial to the project either.	Since I did not see the benefits in using the matrix I probably will not use it again.If I tried using it again, it would be fora complex work project.
4	The only constraint is the functionality of the device and we improved that by sharing our ideas to our customers.	Since the constraint lead the orientation of our design, so I think that affects pretty much.	Constraint matrix is very comprehensive and very deep.	Since the constraint matrix is the orientation of our design, also it shows the constraint of the design. By doing these, team could have a clear target what to do and what not to do.
5	Our stake holder were few.	We used the constraint matrix idea but not the actual excel file.	Did not used it that much past our initial stage of designing the first prototype.	I would use it again for a project or work or personal project that are more complicated and are much more complex.
6	Same reason as above. For the previous question, we weren't able to actually see the poles used by patients so that would be something that I would like to look at further if we were to continue this project.	Again, it confirmed our thoughts on how to proceed with the project. If it was given to us earlier I believe it would have had a greater impact.	I think it is a great format and would be helpful in the future. I mentioned this to Paul a few weeks ago, but I'll repeat it on here: It would be a good addition to the matrix if the rows and sections were summed at the right side. That way, we could easily see which category is the most important! Worth looking into at least.	I think that the format is awesome. I think it could be applied to projects that aren't even design work.
7	The stakeholders box was quite useful. Its presence kept us in check from designing things that would severely negatively affect anyone.	It gave us a good written perspective of what to focus on. Kept our project in focus without a lot of random senseless addtions.	I like the tool - very helpful in identifying constraints. Later in the project, it really puts into perspective what we have accomplished.	I would use the tool in a situation where I have to create something from scratch or near scratch. I work during summers in an R&D department, and such a tool fits in perfectly with the work we do there.
8	The design matrix helped us understand the stakeholders relevance by showing us what constraints might seem most important to the user. there were a few constraints that we knew to focus on because of the constraint matrix. The only problem is, I believe the group didn't refer back to the design matrix enough. We for some reason went with our own tuition a lot.	It worked pretty well when we actually used it, but I don't believe we used it enough when we actually came up with our prototype. I believe the design matrix is something you have to get use to using in order to understand how important it can be used in the design process.	I believe it works and it can help out a lot. I just believe students might not understand taht right away. It was hard to refer to the design matrix consistently instead of just using your own intuition about a design.	I would definately refer to the constraint matrix more often if I had the chance. It seems like a tool that could be very useful, especially since our main flaw was technology and keeping it inexpensive. the constraint matrix would have definately helped us out with this problem.

Continued

Table C.10: Qualitative response data for experimental survey 3 (part 2).

Table C.10 continued

9	Initially we did not consider some of the tertiary stakeholders such as hospital workers washing the gown. Having to sit down and really think about it brought more focus to it.	As I described earlier, for whatever reason not many of our features interacted at all. The ones that did were doing so very slightly. Thus, not much was gleaned from the constraint matrix.	It didn't help us very much, but we all realized that was a product of the fact that our constraints didn't interact very much.	In a more complex situation I think it would be very helpful to have something breaking up and organizing the way its different constraints are interacting.
10	The stakeholders in our design were fairly obvious. Therefore, we did not have to use the matrix very much for this	We knew our design had to be compact, sleek, and lightweight. This could be seen throughout our matrix	It was helpful but it would have been more useful with more instruction on how to apply it to our design	I would most likely only use this for another school project
11	It did not really make a difference to the groups understanding of the stakeholders.	Like I said before, the matrix was especially helpful during the brainstorming processes, however, after that there was little use.	I feel that it is a good tool, however, it did not turn out to be as useful as I had thought it might be going into this process.	I feel that this would be helpful in industry. Especially for showing to my boss.
12	It helped us when we were at a point where we thought we had too many constraints and helped us in figuring out what they all were explicitly and how important they were. However, we did not refer to this matrix often.	The matrix helped us to categorize the constraints as well as possibly develop ideas with technology that may not be available now but may be in the future. Also, it helped us in points of discussion of what our targets were.	I think the matrix has potential to have a big impact but for this project I did not fully realize it with the limited use our team had with it.	I may be doing a design project that will need to incorporate a much thorough outline of these constraints such as in this matrix in the future.
13	The matrix helped to gain an understanding of the stakeholders, but wasn't tremendously helpful since we have to independently determine the stakeholders anyway.	Again, I feel that we underutilized the matrix and didn't use it to its full extent, so it did not have a tremendous impact on our ideation.	Although we didn't use the matrix to its utmost potential, I am optimistic about the matrix and the potential utility that it could provide in the future.	I would be willing to use the constraint matrix again, but I would spend more time evaluating the correlations and values input to the matrix. I feel that this would provide much more value to the matrix as well as a better understanding of how to use the results of the matrix.
14	Before we did the constraint matrix we really only thought about the nurses and somewhat about the patients. The constraint matrix made us think about the company selling it and the manufacturing people too.	Our ideation was mostly done by the time we began with the constraint matrix. We were pretty sure about the features of our design at this point and just wanted to make minor adjustments.	I could see its usefulness in this project I just don't think we used it at the right point in time or integrated it into our design process well.	I think it helps keep competing aspects clear, it's easier than just trying to do this in your head or make a list. I would consider using it for another school project or a work project, I think its best suited to more complex projects.
15	Our stakeholders were very simple, so this was not relevant.	See above.	I don't hate nor love it... It's a tool that didn't have much relevance in our final design, in my honest opinion. Not that it wouldn't in the future, because I feel like it will be important to redesigns (i.e. if we change X, how will this affect Y and Z?).	I think it really just depends on the problem at hand. For a complex design, I feel like the tool would be more of a burden then anything else. But that's just me. For simpler designs, it's a lot easier to get use out of this. However, if I were to try and explain a product to someone, I would definitely use this matrix. It's an excellent tool for that. Any "why" question that they ask about the product can be pretty easily answered with this matrix. Example: Q: Why is it this size? A: Click on the size constraint and show how many other constraints helped drive the final size.
16	Kinda, it rewally jus complicated things more.	Yes actually, we realized we could only go after the individual user.	Again, just another assigment to be completed in the rat race of college.	If I was putting money into a project and really had a lot of skin in the game I would totally use this matrix to help me.
17				
18	It showed them more clearly in the the different areas instead of jumbling them together.	Helped us think through the relations and how we can compromise for multiple groups to be happy.	I think overall it helped.	I think it would really help in more complex designs in industry but right now I don't have any of that complexity.

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Table C.10 continued

19	Once we came up with the matrix, we rarely referred back to it.	It helped us identify the constraints to consider but that was about it.	Apathetic	I would use it just because it doesn't take much time or effort to complete and could come in handy under different circumstances.
20	I feel all our stakeholder data was collected through talking to the end users.	Again, we didn't refer to the matrix after initially completing it and updating it.	I think the matrix was overkill for our design because of its simplicity. I could definitely see it being very useful for a complex design because it has great functionality as an organizational tool. We simply didn't feel the need for advanced tools to organize our design components.	See above. I would consider the matrix for very complex designs and probably very integrated architecture. For school projects, I would likely not find the need for it. Industry might present more situations conducive to its use.
21	The matrix forced us to think about what the stakeholders were but there were not a huge number since it was a product for a specific field.	It really helped us weigh the different designs since we could see how the constraints related to each other.	It was helpful but cumbersome to work with. Also, I feel that the rating system for it was too arbitrary and sometime tough to decide the value. It would have possibly been more helpful to have bigger, more defined ranking capabilities.	I think this would be helpful in developing very complex systems so you can see how a change in some functionality can effect the rest of the system.
22	Visiting the hospital and talking to people helped most.	Once again. It was helpful, but not a huge impact just due to the straightforward-ness and simplicity of our design solution.	It helped get onto paper our most important constraints so that we didn't forget any as we created the final design.	I'd especially want to use it for a more complex design.
23	I think with regard to our stakeholders more research needs to be done to find out truly all who are involved and the nuances of all of our stakeholder's needs. For example, we interviewed firefighters but we didn't get a chance to talk with any bariatric patients. Again, we didn't really use the matrix to it's full potential.	Unfortunately, not very much. It has the potential but I don't think we focused enough effort in the matrix to get much out of it.	I think when used correctly, it could be very useful.	I think there is definite value in it. I may use it again in school projects or industry. I guess we'll see!
24	As I said before, definitively at the beginning it gave us real understating which stakeholders we were supposed to satisfy. Also, talking directly to them was helpful.	Most of its impact has been towards understanding the connection between the constraints and the stakeholders. Hence, we knew were we needed to work on.	I has proven to be very effective. I would just have liked to work more on it, and maybe discussing it a bit more with the TA or the professor to get some feedback.	Probably in the industry, and most likely when working with several projects. As a project manager you want to see which constraints yo up have overall and for each project. Also, since the matrix include the stakeholders, it proves to be a great tool when dealing with a lot of connected information.
25	The stakeholders had some impact, but not a lot in our constraint matrix.	The matrix had no real impact because it was too complicated with unrelated (to us) categories to get an accurate analysis.	Besides showing the complexity of real world product design decisions, there wasn't enough motivation for it to make a difference.	I would only use this if required, or structured and recommended by my employer.
26	We already knew the stakeholders and their interactions so doing the matrix was busy work.	We did not get any major design ideas or revelations with our matrix, and it did nothing to generate ideas or change concerns with the constraints.	I believe that in our case, the constraints and interactions were well known before we started.	I would use the constraint matrix in more complex engineering situations. When there are only a few basic constraints that are relevant, it is not useful.
27	Had one constraint on the matrix that related to this it was called "legacy".	Did relate some constraints that would have been difficult to relate.	It was a little useful. I can see if you were in a real business how it could help a lot more when you have a companies survival based on it.	Dependent upon my job. If my job needed a new product I might use something along the lines of this constraint matrix.
28	It was good to see which constraints impacted which stakeholders. However, assigning stakeholders to constraints didn't seem to fully describe the Needs of the stakeholders.	For this design project, the constraint matrix did not have a substantial impact. Our design process never matured to the level that we were able to benefit from	In general, I just don't think that the constraint matrix communicates enough information to be useful. The levels of interaction are nice to see, but without some kind	I would be likely to use it in conjunction with other tools, or perhaps an iteration of the constraint matrix, but not by itself as is. What would have made the matrix infinitely

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Table C.10 continued

		looking at constraint interactions. It may have been useful if we had reached a point where we were looking to optimize or reduce parts, but due to a slow start and limited design time, the main benefit was just listing and observing the constraints.	of way to assess the quality of a feature or change based on these interactions, it wasn't much help. I would much rather just use a house of quality analysis. See below for some suggestions on how I think the constraint matrix might be made more useful.	more helpful would have been if signs (+/-) could be assigned to the numbers. For example: carrying capacity and lightweight structure have a strong negative correlation, whereas mechanical advantage and ability to be operated by one person have a positive correlation. It would have been helpful to see this - not just how strong the correlation, but also whether it was helpful or a hindrance. Of course, the constraints would need to be phrased in such a way to make this possible. These values could then be summed to provide useful insight. It would be easy to assess whether adding a feature had a net positive impact or a net negative impact on the overall design.
29	The matrix helped us determine less who the stakeholder were but better how relevant each group was. Specifically it helped us narrow down the project to three key stakeholder to focus on; the children, mothers, and hospital staff that deal with the carts physically.	The matrix helped us set up a new design that was more child friendly while at the same time not preventing us from achieving a product that was store-able and more effective in its use of volume.	The matrix proved very good at showing our group what was really important and what could be ignored. It also helped us see what areas contradicted each other and needed to be altered.	I can see using this for my capstone project maybe other larger scale open school project. Industry might see me using this process but again where it's a larger more open ended project.
30	Without having shown the stakeholders our final design, I think we could have made more changes based on their inputs. For our design though, it was quite obvious that the usage and product constraints were the most important.	I think a lot of our decisions were made from the stakeholders' input, but the matrix would be more helpful as we continued to change the design.	I think its useful to have all the constraints written out and organized to see the effects of making a change to one design feature.	I think the matrix would become more useful as you get more experienced with the design process and have a solid understanding of typical constraints and how they effect each other. I feel a lot of the relationships were subjective on how they interacted with each other and prior experience would make the values more accurate; making the tool more useful.
31	It helped us organize a bit what we thought would effect our different stakeholders, but they were mostly assumptions	It partially impacted our designs solutions, specifically when considering what would need to be considered if our product was used for fire situations.	I like it kind of like a whiteboard. It helps to organize your ideas together and makes you actually "say" what the constraints are rather than just going along without defining them.	I might use it for my capstone project which is an assistive device and it could help organize our constraints. I suggested it, but it intimidated my teammates who were not in this class.
32	Most of the information in the matrix (and thus any understanding it provided) was derived from our shadowing and interview experiences. While it helped show how different stakeholders interacted, the interviews themselves were much more illuminating of the stakeholders' issues.	The constraint matrix helped focus us to a productive line of development earlier in the process; without being able to compare it to the same process without it, however, it's difficult to assess how much frustration we may have avoided. The constraint matrix had little impact after the initial direction of the design, though I believe we all held a simplified mental version when making later design decisions and alterations.	I think it was generally helpful, best for forcing the designer to articulate exactly what the boundaries are and the issues to address, preventing oversights from popping up as problems later.	I intend to try using it again the next time I attempt to design a project. Looking back on past things I've made and designed I can imagine several problems I may have been able to anticipate had I had access to a similar tool.

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Table C.10 continued

33	We really only had one stakeholder for this design under the scope of this class so it did not really affect our design much in this case.	As said before we had to change our design considerably during the process and when we had filled the matrix out the first time it helped us to understand that our design was not very plausible in many areas.	I really enjoyed easily visualizing how each constraint affects one another for when future changes can be made. Also just taking the time to specifically think about each constraint for our product helped us visualize our product and how it functions much more.	I would use the matrix for anything in the future that has multiple areas that can be altered by one another and that can be better visualized and understood by using the matrix. I would use it again because I do feel it is helpful as mentioned with how I used it for this course's project.
34	The constraint matrix helped a little bit on understanding the stakeholders relevance to the project. It made us think about how each stakeholder is affected.	The constraint matrix forced us to design ideas according to what our constraints were.	I think the constraint matrix helps with the project.	It would depend on the situation I am in.
35	I felt like I understood the stakeholders' needs before filling out the matrix.	We talked through the constraints more than making use of the matrix to solve these problems.	I didn't feel like it was a useful tool for our process.	Only would use this tool in school.
36	It helped the group some. However, actually putting the prototype in the hands of the stakeholders really focused the group on what our design issues were.	The constraint matrix helped us focus more on what our priorities were and less on what new ideas we needed to develop.	When we completed the constraint matrix, it helped us think critically about the issues that we were facing during the initial design phase. After initial completion, I feel that we could have done a better job of utilizing the constraint matrix.	Again, it gave the group good direction when starting the project. Therefore I would use it again but I would still put the emphasis on presenting our ideas to stakeholders and getting prototypes in their hands in order to get feedback.
37	Our main stakeholder was the user, or Linda. If we were to think about producing this device we would have other stakeholders which are kind of addressed in the matrix. For our device though since we are not planning on producing it the only really important stakeholder was the user (Linda).	It influenced us some, although not as much as our discussions with Linda. Helpful to think about all of the constraints and how they relate but our talks with Linda were much more helpful.	It is a good tool to think about all the constraints and possible how they relate to each other. Probably would have been more helpful if we had been creating a device for a group of users instead of one user because we would have had to make more compromises than creating an ideal device for one user.	Would be interested in seeing how helpful it could be in another project, with a larger group of users. Would be more likely to use it in a school project before industry because I am still not completely familiar with it and it would be hard to explain or teach it to others.
38	Stakeholder impact was focused on a specific group in our case.	Guided us to what aspects the most time and effort should be put into.	Helpful in the design process	It proved useful in our design process. Helps organize and focus efforts. Also gets all the team members on the same page.
39	I helped us organize our thoughts... inherently the matrix can only be filled with things that the user can think of in the first place, but it is a good tool to combine everyone's thoughts in one organized place.	Again, great for organizing thoughts. In terms of generating new information though, since values were arbitrarily assigned (arbitrary in the sense that there are some interactions/values that are hard to correctly specify with our level of knowledge) the matrix did not really tell us anything that we didn't already know.	It is useful, but there were many times when we were filling out values where we felt that the system was too arbitrary. It felt like we were just rating things to give them a rating and not because the rating we gave the element had a huge impact on whether or not the element was going to be considered or not. Additionally there were many times where our rating had to be arbitrary because we don't actually know how important certain factors are or how relative a certain element is to other elements.	I would certainly use it again, but hopefully next time I will have a deeper understanding of all the factors involved on an element and interaction basis so that the ratings assigned to each element can be less arbitrary.
40	For us, the constraint matrix did nothing more than naming the stakeholders. It generally did not impact our decisions.	For us, the constraint matrix did little to impact our ideation. It was helpful to fill out the matrix as an exercise, but nothing more.	I can see how a matrix such as this could come into play when designing a vehicle or another product that has hundreds or more constraints and things that interact but for our simple projects, the matrix was only marginally helpful.	I would not be using a matrix such as this for school projects but I can see how and why it would be used in a scenario where there are hundreds of individuals working on a huge project in industry.

Continued

Table C.10 continued

41	I believe with the gown we already knew who the stateholders were going to be.	As stated above the design matrix made us think of new features and new designs.	It is a great tool and I believe it is most helpful with people who are starting out in design. It helps the new designers through the design process.	I think it makes the designer have to think about all the constraints ans how they might interact with each other. This is very important in design and I believe that any design toll is always helpful. I would use it with a more complicated design project and in another school project.
42	The main stakeholders we thought about were the users and the manufacturers. The constraint matrix forced us to think further into who would be a stakeholder in the product.	We did not really consciously think about the constraint matrix when we came up with the design solutions.	I thought it was a tool to visualize the constraints. Perhaps if we were to go further with the design process, aspects of the constraint matrix would have become more important. For instance the stakeholder portion. That didn't really affect our design, but if we were to try to take it to market and talked with the different stakeholders it might.	Perhaps if I was in a group setting or a manager of a group I would use the constraint matrix, but that does not appear to be how I will start out my career. If I were to use it, it would be in industry as I do not plan to get a masters in engineering or design.
43	Same as with the design problems.	Same as with the previous two.	I feel we had a good design group and would have been able to make the same design decisions without the constraint matrix. Even so, the constraint matrix confirmed these beliefs and would be a good tool to use for groups in need of help or come to a stalemate in their design process.	This depends on the difficulty of the design problem. If I were presented a very difficult problem with many constaints, I definitely would use a constraint matrix such as the one you provided. If the problem was pretty trivial, I would most likely not use the constraint matrix in order to speed up the process.
44	I think it helped out to establish these stakeholders. The basically brokedown your thinking to inspire ideas.	Creating it helped organized our thoughts in the beginning but after that the matrix was rarely referenced	I think it is a good idea because it forces you to break down the problem at hand so you can try and solve it little by little but I am not sure the school environment would be the best place for it because for students it turned into more of a chore rather than a tool	I probably wouldn't with the industry that I am going into but I feel that if I were to use it in the future it would be for more of a complex design because I think for simple things although it is still useful you are kind of just mapping out the obvious.
45	It helped us understand the stakeholders to a point. I feel as though, for our redesign, was that understanding the stakeholders was crucial to know before attempting to do the redesign.	It made us think in a more broad sense. Not just think of one solution and expand on it. We were able to think of many different solutions or ideations and then lower them down to just a couple by using the design matrix.	I feel as though it was a helpful tool in the design process. I like how it expanded our thinking of each individual part of our redesign. I didnt like how many times we had add or take away items from the design matrix. I feel as though the design matrix should be done once, before the ideation begins.	i feel as though this could be a very useful tool in the design process. This could be used in industry to come up with many different solutions, by having all your users, stakeholders and cost constraints on one page. I feel as though this matrix would not be helpful for smaller fixes, but only be useful for bigger fixes.
46	Filling out the matrix forced use to sit down and think about the stakeholders.	Most of the ideas and design solutions evolved from discussions about designs not the matrix.	It has its uses but I would not consider it a critical design tool.	I would use it in situations where I was trying to track user wants/needs through the design process.
47	Our list of stakeholders was relatively short, even after longer periods of consideration time.	There were certain constraints that were much more important than others but I feel that the constraint matrix did not push us in any particular direction that we might have neglected without using the matrix.	After using the constraint matrix, it seems that it would be helpful for more complicated products with a wider audience. It could at least organize the constraints into a format from which all group members could improve their understanding of the design problem.	I would use the constraint matrix if there were more multiple important constraints which worked against one another and at the same time, pulled the product design in very different directions. (such as can happen with a complex design and user base) maybe industry, and more complex projects.
48	mediocre	better understanding of the functions and constraints associated with them help understand incorporating those functions in the design.	Helpful to a good extent. currently design was developed considered primarily the end user needs in mind	

Continued

Table C.10 continued

49	It helped us to show what different people are interested in, and the different views they may have of the problem.	We didn't use it much in actually coming up with ideas or solutions.	I'm not sure how much the constraint matrix helped. We didn't use it much, but maybe just the act of making it helped us to always have certain factors in the back of our mind.	I might be able to if I have a complicated problem at work.
50	there were a few things that i would have liked to do differently to get a better idea of what the product needed to be, such as actually have one of us be put onto the stretcher and really experience what it's like physically as the victim and then as the EMT to gain a better understanding from both points of view	other than listing out constraints initially, we did not go back to the matrix throughout our design process	wish i would have been there for the initial explanation of the tool because i love things like that and i probably would have been more inclined to us it throughout the design	i'd give it a try after a better understanding its overall purpose
51	There are many different types of elderly patients who will use this product so it is hard to say we know all of them. constraint matrix didn't help us examine all of these elderly but we did ID some.	There were some solutions we didn't think of till we made the matrix	Helpful. Forced us to come to a consensus on importance values. We should have used it more.	It was very useful but takes a lot of time to make. Could be useful in industry design and determining the importance of features.
52	The constraint matrix did not impact this very much because it was pretty clear from the start.	It focused us on certain areas that we were able to come up with more solutions to the solutions, and therefore, allowed us to come up with a superior design.	It was a extra work that needed to be done but it did allow us to focus on certain areas more than others.	It depends on the project and if it needed to be evaluated closely or not.
53	The stakeholders were fairly well understood to begin with, but the constraint matrix did help us to understand what things impacted whom, and to what degree	The ideation process was not impacted by the constraint matrix very much, but when it came to combining ideas into an overall solution the constraint matrix was helpful	I feel like the constraint matrix is a useful tool, and now that I have experience using it, it would be more useful in future designs	I could see myself using the constraint matrix in just about any design scenario, but I would be much more likely to use it in a complex design than in a simple design.
54	I believe that we already had a good idea about the stakeholders to this project, but the constraint matrix reinforced the decisions we made earlier.	The constraint matrix forced us to focus on certain aspects of our design. We strictly focused on the parts in the constraint matrix that we believed were most important.	The constraint matrix is a good tool to force additional thought from the groups to consider different problems that may arise in the design process. The ideas put into the matrix had been thought about prior, but having the matrix allowed better organization of our thoughts.	I may use the constraint matrix with future projects in industry. It will help me organize my thoughts and rank what I really need to focus on without wasting a lot of time.
55	For our project we took into account all the relevant stakeholders and we defined our design with all of the in mind.	It was very helpful because it made us focus on few things but with high impact on the final solution.	I think the matrix is a great designing tool.	I think the matrix can be easily apply in the industry.
56	We definitely have a great understanding about our stakeholders and what they need. I don't deny the fact that our design does not meet all their needs but as I said, if we had some more time we could have addressed some more needs and come up with a better design.	We couldn't come up with one main idea regarding what we're actually designing. We had a lot of ideas but did not know how we can incorporate them all together. So, we started from the scratch by making the persona, which helped us in knowing what we're designing and what we're designing. It was still a general idea. It was only after the constraint matrix that we knew who our stakeholders are and what they need. We thought about all the constraints and their importance in the design.	Constraint matrix is very significant in a good design. I think, while making a good design it is very important to know what exactly are the constraints and the level of their importance. Next time I am working on any product design, constraint matrix would be one of my priorities to work on before the actual design.	It would be one of my top priorities to work on the constraint matrix. It will give me the exact idea about all the constraints, be it physical, market, cultural, etc. It will also give me the exact idea about how important these constraints our keeping in mind the stakeholders. As of now, I am planning to work more on my current product design and improve it further. But I am more likely to use it in more complex conditions, to combine all the ideas in the best possible way. It could be used in all kinds of projects.
57	Brought to our attention the various stakeholders that had to be dealt with.	Only the stakeholder impacted our design.	Consider it a waste of time for it to be due. Should be optional.	Waste of time. I guess it would be helpful for more complex projects.

Continued

Table C.10 continued

58	We had a clear understanding of which contstraints affected which stakeholders	The constraints in the matrix really solidified the problems that we had to address when creating our new design	It is useful	I feel like I have seen things similar to this in my past interships/co-ops
59	It helped us see and understand that any change in constraint is going to affect a certain stakeholder.	The matrix definitely had a huge impact on the design solution os our revamped dumpster.	I love it once I finally got to understand how it works.	I would use it again be it for a school project or in the work industry. It helps as a visual aid and helps keep one in focus.
60	The stakeholders were well understood before the matrix but the matrix did assist a little bit	It sort of refocused our ideas on what was really important	Just did not assist to the point that I thought it would. Definitely could be a useful tool but just was not applicable to our project	I would use it in a bit more complex project where there are a lot more stakeholders and each constraint has a much larger effect on them

Appendix D: Populated Example Matrix

1 Photographers

2 Mfg. & Assembly

3 Nikon Corp.

(-) Interaction Depth:	2
(-) Interaction Threshold:	-3
(+) Interaction Depth:	2
(+) Interaction Threshold:	3

ID	NAME	STAKEHOLDER	WEIGHT	DELTA	P	N	T	p1	p2	p3	p4	p5	p6	p7	p8	t1	t2	t3	t4	t5	t7	t8	m1	m3	m4	m5	m6	m7	u1	u2	u3	u4	u5	u6	u7	u8	u9	u10	u11	u12	c1	c2	c3	c4	c5
	Physical Constraints																																												
p1	Size/footprint (-)	1	2	1	18	-14	16		1		4		-1		1	-4		-4					-2		1		3		4	-2	1		-1						1					1	1
p2	Lens mount interface	1,3	4	0	28	-2	12	1		4					2								4	1	2		4		3		3								1			3	-2			
p3	Light tight (+)	1	4	0	16	-1	6		4		3											4			-1		1								4									
p4	Distance lens & sensor (-)	1	2	1	8	-16	7	4								-4	-3			-2															-3						-4			
p5	Material Choice	1,2	2	2	40	0	15			3			3	2	4										3	2	4		2	4	4								2			1	1	2	3
p6	Mold complexity (-)	2	1	1	9	-1	4	-1				3												2	4																				
p7	Weight (-)	1	3	1	12	-14	15					2			-1			-1			-1				1		2		4	-2	-3							-1	-1	-3	2		-1		1	
p8	Rigidity & strength (+)	1,2	3	1	21	-3	10	1	2			4		-1											-2		3			3	4										1			3	
	Technological Constraints																																												
t1	Sensor area (+)	2,3	2	3	17	-23	12	-4			-4						4		-3	4	-3	3		-3	-3	-3	3									3								
t2	Effective megapixels (+)	1,3	1	2	17	-12	9				-3					4			-4	4	-3			-2		4									2							3	
t3	LCD Size (+)	1	3	1	12	-9	10	-4						-1										-1	-2	-1	3				2											1	4	2
t4	Image processing time (-)	1,3	4	4	11	-14	9									-3	-4			-4	4	-1		-2			2															3		2	
t5	Image size (+)	1	3	2	13	-10	11				-2					4	4		-4		-2	-1		-1			2															1	1		1	
t7	FPS shooting (+)	1	3	3	22	-11	13							-1		-3	-3		4	-2		-1		-1			3									3		4		3	3			2	
t8	ISO sensitivity (+)	1,3	2	3	14	-5	9			4						3			-1	-1	-1			-2			3													1			3	
	Market Constraints																																												
m1	Lens compatability	1,3	4	0	22	-3	8	-2	4															2			4		4		-1									4				
m3	Time to market (-)	3	3	1	12	-12	13		1				2			-3	-2	-1	-2	-1	-1	-2	2				3												1			3		
m4	Production cost (-)	2,3	4	0	15	-8	10	1	2	-1		3	4	1	-2	-3		-2							4																			
m5	Consumer price point (-)	1,3	3	1	13	-4	6					2				-3		-1						4																			4		
m6	Compete with Canon xSI (+)	3	2	4	79	0	30	3	4	1		4		2	3	3	4	3	2	2	3	3	4	3				1	1	3	1	2	2	2	1	4	3	2		4	2		3	4
m7	Compatible w/ CLS flash system	1,3	3	1	8	0	3																				1				4								3				
	Usage Constraints				0	0	0																																					
u1	Portability (+)	1	3	1	26	-10	13	4	3		4	2		4									4				1			-2	-3		-1					-4	2			2		
u2	Feel (+)	1	3	1	38	-6	15	-2				4		-2	3												3		-2		2		4	2	4			3	4		4		3	2
u3	Durability (+)	1	2	0	19	-7	11	1	3			4		-3	4								-1				1		-3	2									3			1		
u4	Intuitive menu navigtion (+)	1	3	3	23	0	7											2									2	4				4							4		4	3		
u5	Intuitive physical controls (+)	1	3	2	24	-2	10	-1																			2		-1	4		4							4		4	2	3	1
u6	Start up time (-)	1	2	4	9	0	5																				2			2									2		2		1	
u7	Shutter lag (-)	1	4	3	23	0	8														3						1			4				3		2	3	4			3			
u8	Image quality (+)	1	4	4	36	-3	12			4	-3					3	2										4							3				4	4	2	3	3	4	
u9	AF time (-)	1	3	3	13	-5	7							-1							4						3											4	2	3			1	
u10	AF accuracy (+)	1	3	4	8	-5	6							-1													2											2	-4	1	3			
u11	Shake (-)				17	-7	9							-3							3								-4	3						3	4	2	1	1					
u12	User Experience (+)				60	0	23	1	1			2		2	1						3	1	4	1		3	4	3	2	4	4	3	2	4	4	3	3	1							
	Cultural Constraints																																												
c1	Supported image formats	1	3	2	7	0	4													1							2								2							2		
c2	Similar cognitive structure to film	1	3	0	32	-5	14		3		-4	1		-1					3	1			4							4			4	2	3	3					1		3
c3	Similar cog. Struc. to Nikon point-:	1,3	2	3	16	-2	10		-2			1						1													4	2			3					2	1		1	1
c4	Brand differentiation (+)	1,3	4	2	55	0	23	1				2		1	3		3	4	2	1	2	3		3		4	3			2	3	1	3	3	1		4	1				1		4
c5	Aesthetics	1	3	2	21	0	9	1				3					2										4			2			1								3	1	4	

Figure D.1: Example CCMT matrix populated for a DSLR camera.

Appendix E: Assignments for Student Design Project

BACKGROUND
For the final lab assignment of the quarter you will be asked to identify a design opportunity based upon user research, and ultimately design a prototype that demonstrates your understanding of the many concepts discussed in this course. For this assignment, your teams will be given a great deal of freedom in terms of both opportunity and concept. Accordingly, much of the ideation and research will take place outside the classroom.

TASK 1: IDENTIFICATION OF USER NEED
Your group must identify a specific user class/occupation/context for whom you would like to design a product. Because we want you to develop the skills necessary to design for perspectives other than your own, you should not be a member of your chosen user class. Once you have decided upon a specific class of user (in class), you must conduct primary interviews, with no less than two users, in order to identify needs and design opportunities within their specific context/environment of use. Keep in mind that at least one of these interviewees must be someone that your group can return to repeatedly. You should be using this interview to assess the potential for design in this context/activity, as well as gauging your ability to secure access for the shadowing and user observation.

FORMAT
The format for this assignment will be similar to the persona generation exercise: but rather than including a particular scenario and set of needs, you should be including some of what you talked about with your user as well as a few possible directions that you could take in designing for this user/context.

TASK 2: USER SHADOWING & INDIVIDUAL IDEATION *due week of March 18th*
USER/TASK SHADOWING
As designers it is next to impossible to produce relevant and meaningful design without a good picture of the needs, goals, and desires of users, as well as some understanding of the larger context in which both the user and the product exist. Accordingly, it is fundamentally important that your team spend time with at least one of your users in the actual context/setting of use; this must include a session of detailed observation and discussion (watching and studying what your user is doing while asking questions to build a better understanding of not only what they are doing, but why they are doing it and what they hope to accomplish), and will ideally allow you and your group to get hands on with the activity in question as well. Remember, all of this is done to further your understanding of the user and how your design will fit into their, not your, context.

Some suggestions for good shadowing preparation
Shadowing is made considerably more effective if you can encourage your user to thoughtfully consider their tasks and contexts prior to your interaction. This will allow them to better guide your interaction and discussion during your actual shadowing time; which is particularly important in contexts where you are unlikely to see all of their

activities and challenges even if you shadowed for a long period of time (nurses, police, etc.).

Some **potential** questions to have them consider include (don't overwhelm them):
1. If time/cost were not ever an issue what would you do differently?
2. If cost and weight were not an issue, what else would you carry? Why?
3. What capabilities do you wish you had?
4. What do you enjoy about your task/job? How could that enjoyment be amplified?
5. What pressures (goals, responsibilities, time, safety, errors) do you face on a daily basis?
6. Are there any routine tasks where the current tools/measures are inadequate?
7. Are there any specific scenarios where you are especially concerned with the safety of yourself or the safety of others?
8. Any there any tools that are difficult to use/access when needed?
9. What routine activities are seemingly difficult to perform?
10. What types of tasks do you dread performing?
11. What is your least favorite part of your job/task? Why?

Make sure that you encourage them to think about these questions while they are performing their tasks/activities, as people will say very different things when removed from the context of use. A police officer, for example, is likely to describe what he needs out of a pair of hand cuffs very differently in the police station than he would just after making an arrest in the field. Also, this is not meant to be a survey, and these questions do not need to be specifically answered. Rather, these are questions to think about in preparation for your shadowing. At the same time, if you feel like any of these are particularly important, feel free to specifically ask them during your shadowing.

INDIVIDUAL IDEATION
The generation of an extremely broad set of initial ideas is crucial to the creation of innovative products. Accordingly, one must develop the ability to put aside initial ideas and continue the ideation process (some of your best ideas will come long after you thought you ran out of ideas). Remember, there is no such thing as an idea that is too silly or too far out there; any creative idea can be the spark that leads to another idea or a design concept. For this portion of the final assignment each team member will be required to generate 15 ideas, for products that address your chosen design direction. This may seem like a lot, but I promise that you will see a positive result in your final design.

FORMAT
Your 15 product ideas should be sketched, no more than three to a page, on standard 8.5 x 11 copy paper. As always you will not be graded on your drawing skills, the sketches will function as a communication/visualization tool and must merely get your point across. Sketches should be annotated or accompanied by text in order to provide additional information.

The user observation/task shadowing as well as any hands on practice should be documented in some way to present with your final project. This can be done with video or photographs (take a lot), and some record of key insights should be kept in order to show how your time with the user affected your final design.

TASK 3: COMMUNICATION PROTOTYPE & PRESENTATION
You are required to develop a primary product concept and prototype. You will be required to give a short presentation outlining the product's design, features, and how your product addresses the unique needs of your users. This presentation will serve four primary purposes:

1. Solidifying all of your ideas in a single concept will force you to think through the interactions and synergies between many of your ideas, which to this point existed in isolation. It will also serve as a jumping off point for the rest of your process.
2. The prototype will allow you to think and learn about your ideas in a new way. Ideally you will learn and continue to develop ideas during the process of making your prototype, as well as in interacting with your completed prototype.
3. The class will serve as an excellent source of feedback; asking questions and suggesting possible future directions.
4. In bringing your communication prototype back to your user, the prototype will act as a sort of invitation to participate in the design process. At this stage you will very frequently notice that users transition from answering questions and describing problems to designers themselves—playing with the prototype and suggesting new directions, features, and improvements. Be sure to identify what the user feels works well, what would not work, and what else the design might be able to do, both for the stated task/activity and the other activities in their given context.

Remember to use the presentation as a way to walk the class through your design, and the way that it will impact your user in their unique context—**tell a story of future use**!

FORMAT
The purpose of models at this stage of the design process is to communicate information about scale, form, and usage within three-dimensional space, and to elicit further ideation and feedback from both designers and users. With that said, your prototypes should be reasonably well crafted and must convey their features and intended functionality to potential users, but they need not be fully functional.

Your presentation should be concise (5 minutes max), and will be conducted similarly to the lighting project prototypes (informal, no projector).

TASK 4: FINAL PROTOTYPE, PRESENTATION, & DESIGN SUMMARY
You are required to finalize your product design and produce a final prototype. Additionally, you must generate a two page product summary and short presentation outlining the product's design, features, and how your product addresses the unique needs of your users (pictures are greatly encouraged).

Remember to use the presentation slides as a visual guide to help walk the class through your design process—**tell a story of future use**! Begin by bringing us up to speed on your user and their very specific context, needs, goals, desires, etc., and follow that up with a thorough description of the problem you decided to address (pictures and video are a great way to quickly get everyone up to speed). From there walk us through your design and your final prototype (much of this can be done using your prototype rather than the PowerPoint), with special attention to how your design solved the initial problem with respect to the constraints.

Your presentation should be concise and convincing (~10-12 minutes with questions. Try to make it as visual as possible; strive for few bullet points. Think of your presentation as a tool that you can use in conjunction with your prototype in order to effectively convey your ideas (more about this in class). Also, make sure your presentation is in pdf form!

Your goal for the two page design summary is to convey the value and all of the important aspects of your design in a very concise format. You can use verbal descriptions and pictures in concert with one another in order to accomplish this. In order to condense all of this into such a small amount of space, it is vital that you really consider what about your design is important, and why that matters (what the design does for your user). Your focus should be on outlining each design feature/decision and, in a convincing way, connecting that feature to its benefit in the context of use. In many ways, you should do this before putting together your presentation, as this will be a concise representation of your most important points. This may also require specific pictures/CAD models/sketches/etc. in order to support your ideas.

Attached, at the end of this document is an example of a two-page design summary. Notice the small margins, single spacing and 11 pt font. The challenge here is not having enough information, but rather condensing it into 2 pages.

FORMAT
The purpose of models at this stage of the design process is to communicate information about scale, form, and usage within three-dimensional space, and to elicit further ideation and feedback from both designers and users. With that said, your final prototypes should be well crafted and must convey their features and intended functionality to potential users, but they need not be fully functional.

Appendix F: Two-page Student Design Summaries

B.E.R.D. (Bariatric Emergency Rescue Dolly)

Background:
Firefighters receive many calls with regards to moving bariatric patients in emergency situations. These prove to be very challenging situations which can often result in back injuries. This device is designed to aid in moving bariatric people quickly and safely in an emergency.

Our proposed solution helps by creating a simple solution that recognizes the firefighters desire for simplicity while using the strength of multiple firefighters to help lift a heavy patient.

What exists/competitive advantage:
While there are many existing heavy patient transfer devices, ours provides a unique competitive advantage in that ours is a simple low-cost solution that does not involve motors, and uses the tried and true concept of the dolly for moving heavy objects in collaboration with simple leverage and the power of numbers. While our dolly is not specially equipped to handle stairs, there are other devices that exist with components that could be incorporated to give this type of device a similar functionality, but would go against our design objective of being simple and low-cost.

Compatibility:
With sensitivity to the high expense of medical rescue equipment and the universality of the backboard. We have decided to make a transfer device that utilizes the existing backboard design so as to minimize the cost for fire departments.

Step 1: Place backboard in dolly device and lay it on ground.

Step 2: Place patient on dolly and secure with straps.

Step 3: Insert leverage bars and with the help of 2 people at the head end, lift the patient upright.

Step 4: Lock main wheels in rear position and flip support arm down.

Step 5: Rotate and lock dolly handles in forward position and tilt backward onto the support wheels.

Special Design Features

Hide-away wheels:
The main wheels of the device have two locking positions so that the backboard can lay flat on the ground for loading, and then rotate behind the backboard for maximum support behind the weight when rolling.

Multi-position handles:
The handles of the dolly have two angle positions such that when the handles are locked away from the backboard, they do not impede its ability to lay flat on the ground, and can also be used for lifting the backboard off the ground by 2 firefighters on either side. When locked perpendicular to the backboard they are able to function as normal dolly handles. In future iterations, the handle height can be adjusted based on the operators preference.

Auxiliary wheels:
Two wheels which are stowed along the length of the backboard are locked into place. When the dolly is in its upright position these two wheels can be locked into place to provide extra support for the loaded weight.

Leverage holds:
On the base of the dolly are two leverage holds where a lever arm could be inserted to provide additional lifting power to the weight on the dolly in order to get it into position to be moved.

Backboard-compatible slot:
The structure is designed to hold the existing backboard by easily sliding the backboard into the dolly before loading it with a patient. The structure itself doesn't get in the way of loading a patient down with straps, and the backboard doesn't slip out during use.

Customizable Assistive Claw Device

The user:

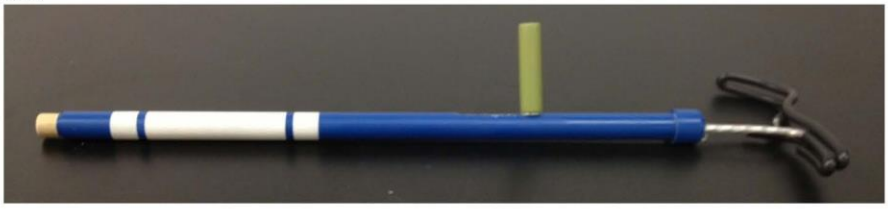
[redacted] is a 78 year old lady who has been very active throughout her entire life. Unfortunately ten years ago she had serious fall which severely damaged her hips and caused her to lose some of her mobility. A wheelchair helps her remain mostly independent but still limits her in performing some various activities. She also suffers from chronic arthritis that has taken away most of the mobility in one of her shoulders. Gardening is one of her favorite hobbies, but it is extremely difficult for Linda due to her lack of mobility. The customizable assistive claw device was designed to be an extra hand for Linda in order to make it easier for her to perform daily activities. Some of these daily activates include pulling a cup across a table toward her, picking something up from the floor, or moving her gardening pots around. This new device will open a whole new range of activities that she was previously limited to perform.

Original device:

The original device that Linda used was helpful but did not give her as much mobility as the new device. The original devices main use was to allow Linda to reach small items that were out of her reach and either push or pull the item towards her. This was helpful but Linda wanted a device that would help her with gardening and also help with more activities that were still difficult for her to perform around the house.

Redesign:

In our redesign we utilized both ends of the new device. One end of the device would be used for general activities that any person in a wheelchair would need help with, while the other end is able to be customized with whatever the person needs additional help with or enjoys doing. In Linda's case she enjoys gardening and any gardening tool that she currently uses could be slightly modified and be able to be attached to the new device. The end used for general activities is the end on the right side of the figure and is the "claw" mechanism, and the trigger for the "claw" can be seen in the center of the picture and is shown in green. The end on the left side of the figure is the customizable end, and many different tools can be added and switched on that end.



"Claw" Redesign:

On one end of the device is a pair of semi-flexible wires bent in a very specific shape. The main purpose of this end is to provide means for pushing or pulling objects that are out of reach for the user. A key concept here is versatility, as one cannot predict every situation that the user will encounter, however the pictures showing the water bottle below demonstrate how the user can reach objects without having to move from their previous position. The smaller and larger bends in the wire form provide greater control over the object being maneuvered, while the rubberized coating ensures that any objects of value won't be scratched or damaged in any way during operation.

The larger rigid piece of wire constitutes the main pushing/pulling device, while the smaller movable piece enables the user to grasp small objects that may have fallen on the floor or are stored out of reach without requiring the person to move from a seated position. This mechanism utilizes the hollow center of the PVC tubing to store a rubber band driven, slotted knob actuator. A cropped-view rendering of this mechanism is shown in the middle picture below, with the rubber band (pink) resting in a slot on the slider (green) and held in place with a cotter pin at one end of the tubing. The rubberized coating on the wires, in this case, serves to provide extra gripping power while attempting to grasp objects. The gripping wire form itself can also be reshaped, since the wire is semi-flexible, to adapt to different gripping situations.

The end of wire opposite the gripper is bent downward in order to provide means of storing the device while not in use. This small detail is crucial for usability, because the user must hang the device on a walker while transitioning from a wheelchair to standing with the walker. If the device happens to fall on the ground during this transition, it will be extremely difficult for the user to bend down to reach the device from a standing position.

Customizable End:

On the customizable end of the device is a wooden piece. This wooden piece is needed to enable a variety of different tools of be able to be attached to the device. To show a variety of different tools that could be attached to this end we created a broom attachment and attachment of a hook. Linda asked for a broom attachment, and also asked for an attachment that could be used to make use of her oven easier. Linda can use an oven but often has trouble safely pulling the oven rack out to get her food out of the oven, this hook will allow her to safely pull the oven rack out and also allow her to push it in once she is finished. Linda enjoys gardening and her garden tools could easily be modified to be used with this device. As seen in the picture on the right, the only modification needed to current tools is to add a screw, which can then be securely screwed into the wooden end of the device, and the device can be used with any tool that the user desires.

Emergency Stretcher for Large Victims

Background: Fire departments are frequently called to assist victims that have fallen or need help in their homes. A large percentage of the emergency calls come from victims that are overweight. The firefighters are in need of a stretcher or contraption that puts less strain on them when helping these heavier patients. One prominent struggle the firefighters face with heavier victims is the physical act of getting them on or to the stretcher. **Redesign:** It was decided to redesign the current stretcher as two modules, the backboard and the stretcher frame. Our redesign puts emphasis on getting the patient from the floor to the backboard module.

The Backboard—Teetered Backboard

By designing the backboard to teeter to one side allows the firefighters to roll the victim on their side and slide the angled backboard underneath. The weight of the victim assists in rotating the backboard to a horizontal position. This eliminates the need to lift the patient onto the backboard, reducing both the time needed to move patients and the physical strain on emergency personnel.

The Backboard—Handles

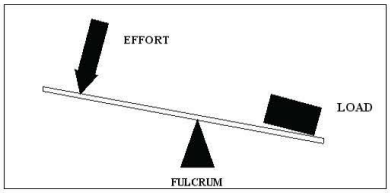
On the front end of the backboard module there are shopping cart – like handles. The handle is designed to be raised up above the height of the backboard, eliminating further strain on the firefighters from having to bend over to move the victim onto the backboard. With additional handles at either end of the backboard, two men can push and/or pull the backboard where necessary. Like on existing backboards, the redesign still includes side holes for firefighters to utilize. These side handles allow for a "team lift" when the victim is somewhere that the whole stretcher cannot fit and only the backboard can be used to transport the victim.

The Backboard—Locking Wheels

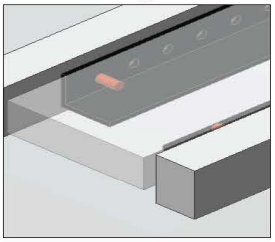
For more maneuverability of the backboard itself, the redesign includes 4 locking casters on the underbelly. In some cases, the existing stretcher cannot physically fit in all sizes and shapes of rooms. Having wheels on the backboard module allows the firefighters to move the patient around with ease to another room where the stretcher is set. The four wheels on the backboard are capable of being locked. It is essential to ensure that the backboard does not roll around as the firefighters are loading the victim onto it.

The Frame—Pivoting Tracks

Once the victim is secure onto the backboard, the backboard rolls onto two angled tracks that line the inside of the frame. The track angle makes loading the patient onto the stretcher much easier by eliminating the need to lift the patient. The backboard can be simply pushed into the frame, and the tracks guide it into position. A pin placed just past the center of the tracks acts as the fulcrum. Once the loaded backboard reaches a certain point, the tracks pivot at the pin into a horizontal position. Once the tracks pivot into the horizontal position, a pin at the back of the frame stops the tracks from going beyond horizontal. After this pin stops the tracks in the horizontal position, the backboard and tracks can be locked in position.



The Frame—Locking Mechanism



To ensure that the backboard does not slide out from the frame, locking pins are implemented at the end of the frame. Pins are placed from the outside of the frame, through the pivoting tracks, and finally behind the wheels on the backboard. This eliminates any translational or rotational freedom, and keeps the patient in a stable position. After the backboard and tracks have been locked into position in the frame, the stretcher functions exactly as any of the normal stretchers in service now would. Hydraulic or pneumatic assistance may be used to raise the stretcher so that it can be easily maneuvered and loaded onto the ambulance or EMT truck.

Underwater Communication Device – The "ScuBuzz"

By: [redacted]

Problem Background:

Radio Headset

Tank Banger

Getting a person's attention in an underwater setting, such as while scuba diving snorkeling, is important in many situations. For recreational divers, there are two popular methods to do this. The expensive method is for every member of have their own radio, which allows everyone to talk to each other while The inexpensive method is to make a sound using a tank banger (shown on the making an 'O' shape with one hand and hitting it with the other. The expensive costs around $1500 for each unit and each person needs a unit in order to communicate. The inexpensive method does not tell the direction of the noise or made the noise because of the speed that sound travels underwater—it can also extremely difficult to notice, and has a very limited range.

or currently the group to submerged. right) or by method who be

The New Design:

The ScuBuzz

We chose to integrate some simple features into watch-like device allows for quick and intuitive communication between wearers by vibration and LED's when certain functions are activated. The device also point the wearer towards the direction of whoever is trying to attention. This is a very helpful feature for more critical situations. this particular design would be best suited for scuba divers or a multitude of situations where communication needs to be quick effective. The design is a significant improvement over the primitive making methods that currently exist and it is cost-effective enough to accessible by anyone.

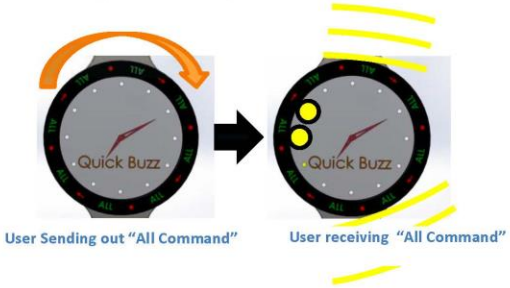
that using can get their We believe snorkelers in and noise be

Feature #1: "Quick Buzz" Button

This feature is located on the face of the watch can be pressed to cause all other devices to instantaneously. The other devices vibrate only as the button is held down. This can be used to get everyone's attention. This function is very adaptable in that it allows the user to define its purpose as a communication tool. An example of could be Morse Code or some other type of code the users desire.

and vibrate long as quickly this that

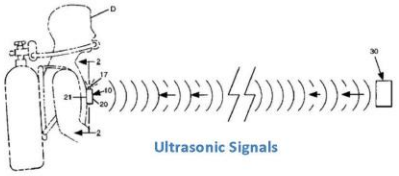
Feature #2: All Command (using bezel rotation)



When the bezel of the device is rotated 90 degrees clockwise, all other devices vibrate and LED lights around the circumference of the devices light up, indicating the direction of the user who activated the feature. This command is distinct from the "Quick Buzz" function because of its unique flashing lights and continuous vibrating pattern. This vibration can be turned off by the person receiving the signal by simply pressing the face of the watch. Although this command is also user-defined, common signals may include the time for everyone to surface, or a signal for help. Constant flashing LED lights and a bezel activation that is unlikely to be activated on accident implies that the "All Command" will be used as a more serious signal than the "Quick Buzz."

Technology:

The ScuBuzz will rely on a built-in ultrasonic transmitter and receiver for the "Quick Buzz" and the "All Command" functions. This technology is based off a patent for a "Homing Device for Underwater Divers." [(1)] This allows every ScuBuzz to communicate location and basic on/off functions. These abilities of provide the immediate vibration response and location the device.



The ultrasonic transmitter/receiver combo works similarly to sonar. However, both are not required for the "Quick Buzz" option. Therefore, when the button on the face of the watch is depressed, only the receiver function will be activate, saving battery life. The directional LEDs will only operate when needed in the "All Command." When the sonar from one watch sends out a signal, the receiver will pick up the noise and triangulate the signal to determine from which direction it came. Then, LEDs will light up the face of the watch and point to the signal's origin.

[1]http://www.google.com/patents?id=juolAAAAEBAJ&printsec=abstract&zoom=4#v=onepage&q&f=false

Portable Gas Can

Portable gas cans are a necessity when it comes to performing landscaping activities. These cans are used by a variety of people, ranging from professional landscapers to household families. There are a variety of different styles to choose from; however none of the current designs are user friendly. Due to updates on EPA regulations passed on January 1, 2009, every portable gas tank must conform to the following regulations:

- There must be a single, self-venting opening for filling and pouring with no separate vents or openings.
- The can body must be treated for minimal permeation of fuels.
- There must be an automatic closer, meaning the nozzle must automatically spring to the closed position when not pouring.
- Child-proof features as designated by the "Children's Gasoline Burn Prevention Act" (ASTM F2517-05)

These regulations have added additional struggle when it comes to usability. There are numerous problems with each of the current gas tank designs. The user complaints included insufficient handle space, non-intuitive design to open the nozzle, poor nozzle venting, and the hassle of having to use two hands to hold the nozzle open while pouring.

Redesign:

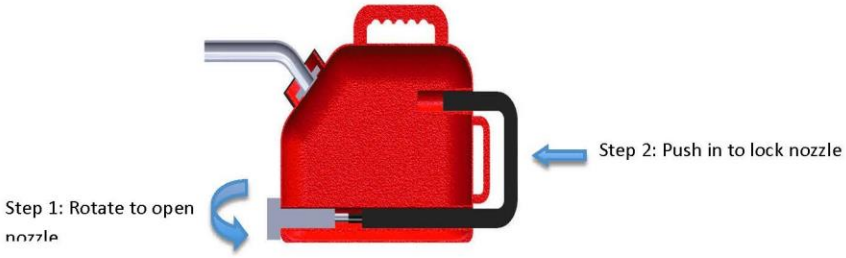
We choose to redesign the portable gas tank because this is a tool that is commonly used in every household, along with professional landscapers. Our redesign is focused on allowing the user to hold the nozzle open and pour while only using one hand, thus freeing up the user's second hand to hold a funnel or to help support the weight of the gas can.

Handle Redesign

Currently, the handles used on a lot of the gas tanks are extremely restricting as to where the user can hold the can. In order to eliminate this as a constraint to the user, a combination of side and top handles that wraps around the majority of the gas tank will be incorporated. This will allow the user to comfortably hold the gas tank in whichever way is most comfortable to them.

Integration of Handle with Valve Opening

Most of the current designs force the user to remove one of their hands from the handle in order to hold the nozzle in the open position. In order to resolve this issue, the mechanism that holds the nozzle open is integrated into the handle itself. This allows the user to keep the nozzle open by holding the gas tank at any point along the back handle. There are also no buttons or levers that would normally constrain the user on where they can hold the gas tank.



Closed

Open

Revamped Dumpster

Trash dumpsters are an underappreciated but essential part of society. Whether for personal or commercial use dumpsters serve the same purpose, storing rubbish until it is removed by a garbage truck and disposed of. Some of the problems encountered by dumpster users include the pungent smell emanating from dumpsters, difficulty putting trash into the dumpster, and difficulty in emptying the dumpster.

Redesign

We chose to redesign a residential trash dumpster. Two user groups were considered during the redesign of the dumpster, individuals throwing away trash and garbage truck drivers emptying the dumpsters. Our redesign focused on keeping out rain and ease of getting the trash into the dumpster. The redesigned features were the roof, windows, and general shape of the dumpster.

Overhang Roof

As it stands now, the roofs/lids of the dumpsters easily let rain water in because in most cases they are left open by users. Our team designed an extended roof that covers the surface area of the dumpster. This is beneficial as it protects the contents of the dumpster from environmental factors such as heat and rain. This new design feature reduces the amount of moisture and heat the garbage is exposed to which reduces the smell.

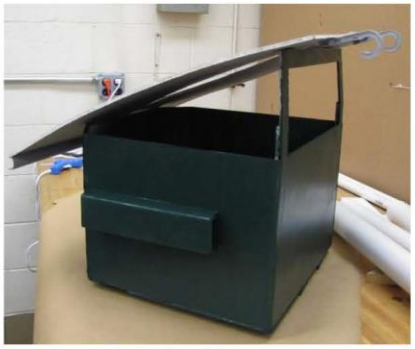
Current Dumpster Design

Redesigned Dumpster

Open Windows

Current dumpsters have few openings which make it harder to throw trash. Our design team added an open area to the sides and the back. This new design feature ensures that air circulates within the dumpster and one can easily dump trash into the container. Another added benefit is that users do not need to touch the dumpster or even go as close to it.

Current Dumpster Design

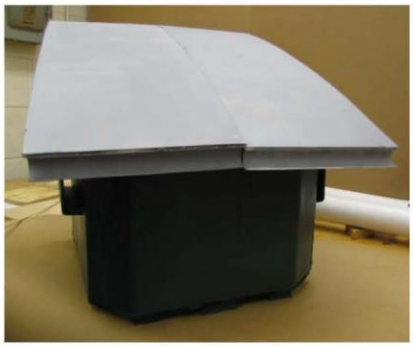


Redesigned Dumpster

Shape

A common feature of dumpsters is dents and scratches on the side caused by garbage collection trucks. This is because the current shape makes it harder for the drivers to properly grasp the dumpster when trying to empty it. The redesigned shape allows garbage truck drivers to easily grasp and lift the dumpster with their fork lifts. The advantage is that this new shape minimizes deformation of the dumpster on the sides caused by the trucks. It makes it easier, faster, and efficient for truck drivers to do their job.

Current Dumpster Design



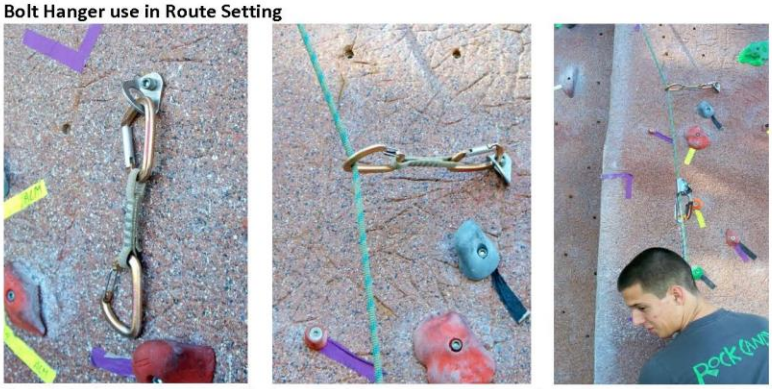
Redesigned Dumpster

Path Changing Device (PCD)

Route Setting

Routes are set along the vertical line connecting the ground and the top rope anchor. The setter does not make a route that deviates too much to the side of this line to reduce the risk of swinging if the climber were to fall. However, the route setter may want to make a diagonal or zigzag pattern for added difficulty as long as it will be safe for the climber. When placing a hold that is far off to the side, the setter has to fight a strong horizontal force from the rope. They can no longer screw in the hold comfortably and have to reach to the side to screw in the hold which can cause added fatigue.

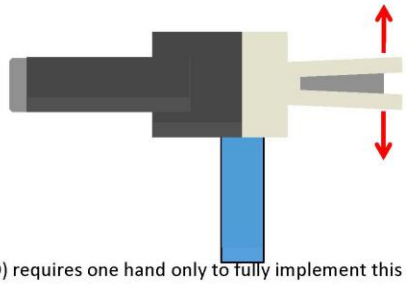
Bolt Hanger use in Route Setting



Currently the route setter will place a bolt hanger two to three feet above the desired location of the new hold. They will then put a carabineer in the bolt hanger and put the rope through the carabineer. The setter is still attached to the anchor at the top. The carabineer simply redirects the path of the rope and takes the horizontal force off of the setter. The setter is now hanging in front of the desired hold location.

Redesign of Bolt Hanger Concept

Our main design problem was to create a product that would improve the route setting process. This product needed to be as intuitive and easy to use as possible. Our design promotes a quick install procedure as opposed to screwing a bolt hanger into the wall.



The Path Changing Device (PCD) requires one hand only to fully implement this device in place. The device uses an expanding screw concept to lock itself in the T-nut. The device is completely integrated as one body. The body of the device that actually expands inside the t-nut is coated with a rubber body to protect the threads coming into contact with it. This is the only modular part of the device. This rubber coating is low cost and can be discarded and replaced when it wears out, increasing the longevity of the actual device.

Using the PCD

The route setter would carry two or three PCDs with them on their harness when they start making a new route as well as all the holds, bolts, and tools needed to make the route. He or she would ascend up and start placing the different holds for the route that is preferred. When reach a place where the hold is beyond arm's length or when they come to an overhang, they would grab one of the PCDs off their harness. They would put it in an unused hole in the wall, push the thumb button in and lock it in place. They would then feed their rope through the bolt hanger that is attached to redirect their path. The route setter is now hanging in front of the desired hold location. If the setter chose's to be back in the original path then they can take the PCD out of the wall and fall back in line with the original path.

Value Added

The PCD reduces time require to place a device in the T-nut from 20 seconds with the bolt hanger to approximately 3 seconds using the PCD. Also, it eliminates the use of bolts. It reduces the probability of wrist injury caused by the screwing motion used in installing a bolt hanger and is therefore more ergonomically favorable. In addition, it is easy to use even if the user is a less experienced route setter. Finally, the design minimizes the damage to threads by using a protective rubber coating.

Nationwide Children's Patients' Cart

At use in the Nationwide Children's Hospital in Columbus, OH are a fleet of more than 60 very large, bulky, and inconvenient wagons that patients use for transport of children and materials.

These were found to be very problematic around the hospital as they lacked maneuverability, storage efficiency, and safety for patients. We found the main issues with the wagons to be the need for pulling the wagon, the wagon being high off the floor, and the only way of storing these takes a great deal of space.

To fix these main issues, we focused on redesigns of using small wheels, incorporating some type of stackability, and making the base of the storage low to the ground. We also attempted to make the cart as kid-friendly as possible by adding decals to give the impression of a racecar.

Redesign 1 – Small Wheels / Low Base

The small wheels were used on the revised "cart" instead of the large ones on the wagons in order to prevent the carts from being stolen while still allowing easy movement on the flat, tiled or carpeted floors of the Hospital. The low base is beneficial to keep safety a priority for the children that may travel in the cart. The wheels provide a "bearing" like maneuverability to the cart for ease of use.

Redesign 2 – Stackability / Push instead of pull

The stackability was prioritized through the redesign so that the storage issues for the hospital can be solved. While improving space efficiency, the stackability was used to help patients of the Hospital have ease of use in pulling out the cart from the stack and use it right away in the hospital. The storage efficiency also helps the nurses, workers, and volunteers clean up after the users as quickly as possible.

To accomplish stackability, the back of the cart folds down into the base; this base and back stack is lifted by the cart that is pushed in behind it with a short ramp on the front of the cart. A brake was also incorporated in order to keep the cart steady while children climb in or as the parents store their materials.

Redesign 3 – Appeal to Children

This aspect of the redesign mainly consists of encouraging children to climb into the cart without necessity of instruction for the users. The aesthetic appeals should also keep children occupied enough to not be a hassle to the parents. This will also keep the products' lifetimes longer while children are excited to take care of the carts.

Hospital Gown Redesign

[redacted]

A hospital gown is a short sleeved, thigh-length garment worn by patients in hospitals and other medical facilities. These gowns are usually made of cotton and designed to withstand repeated washing in hot water. Hospital gowns are usually closed by two ties, one located on the top of the gown and one located in the middle of the gown.They also contain snaps along the top of the shoulder and sleeves, so that the gowns can be more easily removed. The gown redesign was approached from two angles; Problems with the gown itself and other problems within the hospital that the gown could help solve. On the gown itself, telemetry boxes (heart rate monitoring devices) were frequently lost in their pockets and the closure system was inadequate and difficult to use. Patient movement assistance, catheter bag storage, and call button integration were three problems that were identified and attempted to be solved with the gown.

Redesign:

With the number of users that interact with the gown (nurses, hospital workers, patients, etc.) and the number of problems that could be addressed, the hospital gown seemed like a great product to redesign.

Telemetry box redesign:

Currently the telemetry boxes are placed in a pocket, made out of the same cotton material as the rest of the gown, located on the front of the gown. The cotton pocket caused the telemetry box to be frequently lost (Elderly patients unknowingly leaving with it, boxes going through the wash, etc.). The solution was to replace the solid cotton pocket with an easily transparent, coarse mesh. By doing this the telemetry box will still maintain its functionality, and be more easily found by the hospital staff. With an easy visible pocket, other devices may be placed here for easy storage and visibility.

Catheter bag Redesign:

In a hospital setting, when a patient gets up to go for a walk, patients would have to carry the catheter bag or secure it to their leg. This could be unsettling for the patient to carry a bag of their own urine. Additionally, many feel uncomfortable with their urine being visible to all onlookers. As such, we have made an insulated hidden pocket located on the interior of the gown. This will allow the patient to carry the catheter bag hidden from sight while also not being uncomfortable.

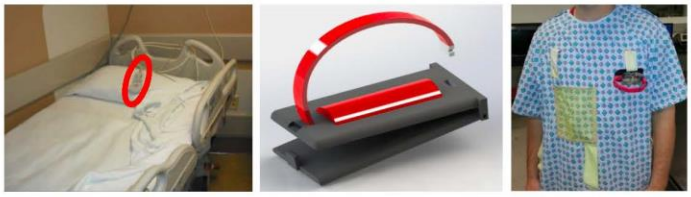
Attachment loop Design:

Currently, moving patients out of bed, and adjusting patients in bed can be very difficult for nurses. In bed, a patient must roll back and forth until a nurse can fit a towel underneath them to move them. It could take up to two to three nurses to move patients depending on their size. Many patients in a hospital will need to undergo physical therapy or rehab of some sort where they are assisted in walking. Knowing this, we have placed multiple loops around the gown at waist level. The multiple attachment points can allow the nurses to not only move patients with ease, but also keeps the movement assistance band on the patient at all times, no matter how much the move or toss and turn in bed. These bands are optional, and may be placed through the loop depending on if the patient requires extra movement assistance or not.

Closure system Redesign:

Currently, hospital gowns are closed by two ties on the back of the gown, one at the top by the neck, and in the middle by the waist. They are very secure, but hard to tie for some patients and offer no adjustability. Our addition of the catheter bag pocket makes closure strength very important. Thus, we retained the tie closure at the top of the gown by the neck. The waist level closure has been replaced with a belt and clip closure. The belt starts at the back of the gown, wraps around the front through the loops, and clips to the desired loop. The belt closure is intuitive and familiar, functioning identically to an oversize pants belt. The clip on the end can be taken on and off quickly and allows for size adjustment.

Call button Redesign:



Traditionally, call buttons have been located on a remote which is attached to the bed. It is common for the remote to get lost amongst the sheets or fall in between the mattress and the bed sides. The multi-functionality of the remote (TV remote, call button) also confuses many patients. The inclusion of the call button as part of the gown became a very logical conclusion. Our design features a removable call button that clips on to the loops that were described earlier. It can be moved at the nurse or patients discretion, perhaps to avoid a sensitive area post-surgery, and removed so the entire gown can still be washed. The call button is activated by simply pulling the loop away with one swift movement, which is easier to use than depressing a small button. It also gives the user concrete feedback that they did in fact activate it both with the visual confirmation of the torn away loop and the activation of a blinking LED. A security measure is also in place with the new call button feature, where a nurse may secure the loop to the bed to alert them if the patient leaves. Finally, a call button on the gown allows the patient to call for help from anywhere (such as a bathroom or in the hallway), not just at their bed.

Integrated Bike Safety Light

Figure 1: Integrated Design (Shown Retracted)

Figure 2: Deployed at night

Initial Problem

Safety is an important issue for bicycle riders today, especially at night. Current bike lights do a poor job of illuminating the rider, and do a poor job of alerting motorists to the presence of a bicycle. Motorists easily lose sense of how far bikers are, because normal bike lights consist of only a single point source of light. Even the best lights have only a few LED's spaced less than an inch apart. At the same time, these lights do not illuminate the rider at all, and are easy to steal.

Redesign:

With our design, we wanted to develop a new style of bike light that would fix the issues mentioned earlier. First, we needed to give the perception of width to the rider, meaning that the lights needed to be spread out, so that motorists have a better idea of the size of the bicycle and rider. Next, we wanted to illuminate the rider, again aiding in recognition of the bicycle and rider for the motorist. Finally, the light needed to be integrated onto the bicycle in order to prevent theft. After reviewing these criteria, we came up with the following design shown in Figures 3 and 4.

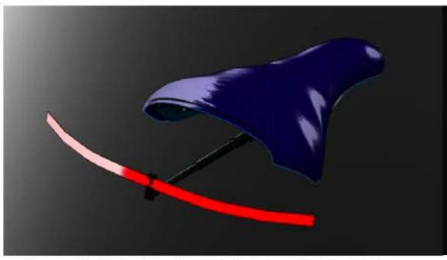


Figure 3: Light Deployed & Rear-facing LEDs

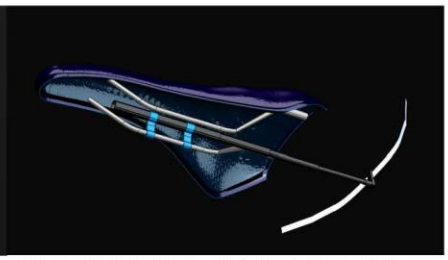


Figure 4: Light Deployed & Front-Facing LEDs

LED Strips:

By using strips of LEDs instead of single LEDs, the goal of giving the perception of size to the rider is accomplished. Here there are two strips of LEDs used, a red strip in the back to alert motorists, and a white strip in the front, to illuminate the rider as shown in Figure 2. These LEDs are mounted to flexible "wings" which easily deploy behind the bicycle seat.

Telescoping Design:
The wings that contain the LED strips are mounted to a telescoping arm. The telescoping arm is mounted underneath the seat. When it is extended, the wings are behind the rider, giving them the ability to bath the back of the rider in white light. When retracted, the apparatus is neatly tucked underneath the seat. This prevents theft and keeps the light out of the way of the rider. This arm is spring loaded, giving it the ability to be quickly retracted in order to keep it out of the way of the rider when dismounting.

Figure 5: LED Strips (Front Strip Shown)

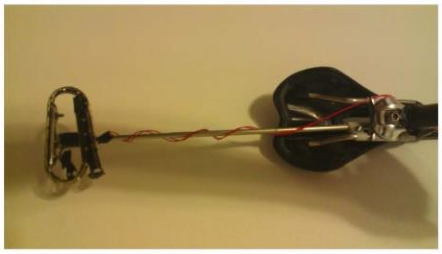


Figure 6: Telescoping Design

Mounting Points:
In order for the light to be mounted to almost any bicycle, a universal mounting system had to be developed. Most bicycle seats are attached to the bicycle post by two rails running underneath the seat. Our system uses two clips that attach the telescoping arm to these rails, as shown in Figure 4. This gives the user the ability to mount the telescoping arm either underneath the seat, outside of the seat, or underneath the rail.

Wiring Harness:
In order for the installation to be easy, the wiring must be pre-arranged into a wiring harness. The harness will include the wires going to the LEDs, a switch activating the LEDs, and a mount for the battery. The switch and the battery are hot-glued to the seat in our prototype, but in production would most likely use 3M adhesive backing for mounting, or have them integrated as in Figure 7.

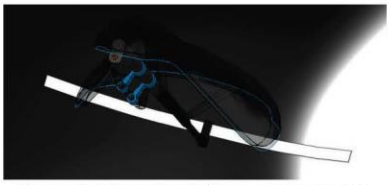
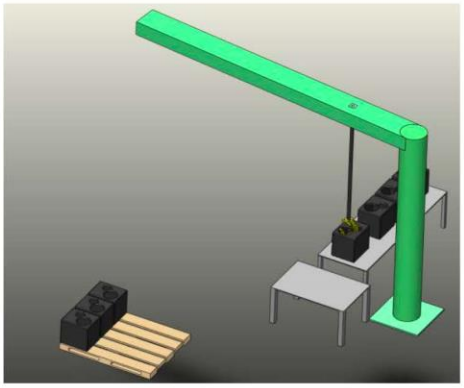


Figure 7: Integrated Battery compartment

LIFTING ASSISTANCE DEVICE



At the Honda Transmission Plant operators are required to lift and maneuver transmission cases weighing about 15 pounds. Parts come off a conveyor every minute after being die casted. The operator must then reach over a table to pick up the part off of the conveyor. Then he/she must file the part, and scan it. Lastly, the operator must carry the case and walk over to the pallet which is located behind him/her. This task can become very strenuous when repeated continuously throughout a shift.

Design:

We chose to design a device that would assist an operator in lifting and maneuvering transmission cases. The device allows the operators to perform the same tasks, just with assistance. It does not add any additional time to the process. Our design focuses on simplicity and ease of use. With these goals in mind, it has the potential to be applied to other operations.

Spring/Gear Mechanism:

We used a torsional spring and gear mechanism to aid in the lifting of the device. This mechanism can allow the operator to pull down or lift the transmission case to any height. The size and stiffness of the spring determines the weight that can be supported by the device. As the string is pulled the spring unwinds to the other gear. When the string is released, the spring rewinds back to the original gear. It is similar to a cassette tape.

Hook:

The hook is the part that attaches to the transmission case. The simple shape allows it to be used for all types of transmission cases and can be attached to a variety of features on the transmission case. This allows for the process to require no additional time. The hook is rubber coated. This keeps it from scratching the case and creates friction so that it stays in place.

Track:

The overhead track allows the user to slide the spring gear mechanism and transmission case across the floor to the location of the pallet. The track can also rotate, increasing its functionality. In the prototype design this track is attached to a pole. When actually implemented at Honda we would look for existing structures to attach the track to.

Handle:

The shape of the handle makes this device comfortable and intuitive to use. It also serves as an added safety feature. It uses electrical controls to lock and unlock the system. When the operator squeezes the handle, it allows him/her to freely move the transmission case. Once the handle is released, the track and string are locked in place. This allows for no movement unless the operator is controlling it.

Usage:

To use the device the operator must squeeze the handle to send an electrical signal to the track and spring mechanism, this will turn off the safety lock. The operator can move the hook freely. Once the transmission case is on the hook the operator must assist in the movement of it, in order to counter the spring force. After the handle is released the safety lock is turned back on, and the device can no longer move.

Light Sash

Adequate lighting is a necessity for many occupations that operate in low visibility conditions. This includes not only visibility for each individual, but visibility of the individual to others as well. One such occupation that has these requirements is that of the police officer. Many officers will find themselves working in conditions with poor lighting such as inside of poorly maintained structures or at night. Depending on the situation, officers may need to be able to effectively illuminate their surroundings, but also be able to display their own location and status to those around them. An example of the latter is in large crowd control situations where officers must be able to quickly and accurately determine where fellow officers are in order to maintain control. Currently available personnel lighting options are limited to reflective vests which offer limited visibility since they produce no light of their own.

Redesign:

We chose to redesign police after meeting with several officers and them expressing an inability to locate and identify each other in crowd situations. After looking on the market we were unable to find any devices that actively illuminated an officer for easy and quick identification. Looking further it came to our attention that the horses that officers many of times use in these situations could easily be lost in a large enough crowd under low lighting situations.

Sash Design:

The sash was chosen because it combined both the features light weight and maximum visibility range. The sash being over the shoulder allows for people to see the person from multiple angles and different vantage points.

Chest Light:

The Light on the chest is turned on and off by the white button in the middle of it. This light is on a different circuit that the light strips so that it can be turned on and off individually of all the other lights.

The main purpose of the light is to allow the person to see objects that the officer is interested in while having his hands free for other task, such as writing a ticket, inspecting a vehicle and apprehending a person.

Multiple Light Settings:

The controller would allow the officer to have the lights do a variety of functions that can range from having them do a strobe pattern, flicker, and pulse. Then all of those are able to be done at a variety of brightness. This allows the officer to use it as a way to attract attention from the crowd around him or a way to signal to other officers in the

Velcro Attachment:

The sash is able to quickly put on with ease and stay on securely. The reason for Velcro though is to enable it to come off if tugged at. Many of times if an officer is in a struggle they want to reduce as points on them that the assailant can grab at and gain an advantage over the officer.

Multiple User Groups:

One of the issues that was addressed was that the officer's mounted units were also hard to see in the low light situations even with their size. The sash can be easily taken and wrapped around the horse's neck to allow for people to help identify the horse and officers to quickly scan above a crowd to find them.

Lighted Magnetic Mechanic's Tool Organizer "Poindexter Companion"

Magnetic trays are widely used by mechanics for holding tools and parts while working. These small trays are made of sheet metal and have magnets attached to their base. They can hold a limited number of tools and parts in a rather cluttered area. When working, speed and efficiency are very important, and these trays slow down the user by having him dig through an unorganized tray. They fill up quickly and make it easy to misplace tools. There are also a number of solutions for under the car lighting, but they are usually their own devices, and are sometimes not used because it is inconvenient to bring something extra under the car.

Redesign:

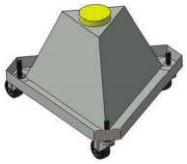
For this project, we decided to take the original magnetic tray and improve its organizational abilities and add wide area lighting for under the car. This solution allows a mechanic to stay organized and work faster while in a variety of conditions.

Vertically Sloped

We chose to redesign the geometry of the magnetic tray in order to provide a more efficient use of the space available to a mechanic while working in close quarters. The redesigned magnetic tray offers a generous area to place not only fasteners, but also tools. This was accomplished by making the magnetic tray a tetrahedron shape allowing the mechanic to see the contents of the tray without having to look into it. This also allows for better organization as it provides the mechanic with three separate sides to put tools and parts on.

Caster Wheels

To allow the mechanic to easily access all three sides efficiently, caster wheelers were integrated into the design. This not only allows the tray to be rotated easily, and therefore increases its organizational capabilities, but also allows it to be transported without having to pick it up. Finally the tetrahedron construction allowed for only 3 caster wheels for stability, instead of 4, which would have resulted in unwanted wobbling of the Poindexter.



The Trays

Speed is a major reason for the redesign of this product. To increase speed as much as possible, a nonmagnetic tray surrounds the bottom of the product. This tray provides a place where small parts and tools can be quickly tossed if needed.

Color Coding

Integrated into the design is a color coding scheme. The color is placed on the outside of the tray so as not to be scratched by the tools inside it. This color coding scheme allows the mechanic to quickly assess which side of the magnetic tray needs to be accessed and in which direction it needs to be turned in order to acquire the needed part or tool in the least amount of time.

Invertible design

Mechanics work underneath as well as above the vehicle. Although this tray is primarily to be used underneath the vehicle, the tetrahedron shape of this magnetic tray allows it to be used above the vehicle as well by simply inverting it and using it as an open topped container.

Removable Lighting

Lighting for this tray is designed to be customizable. Three magnetic lights can be attached to the top or sides of the magnetic tray. This gives the mechanic a variety of lighting options to cater to a wide variety of working conditions.

"Maglite MAXX"-Light Supplement Attachment for Maglites

Maglite flashlights are a standard tool used by every police officer while on duty. With the range of equipment that policemen must carry on their belts at all times, it is of utmost importance that each individual tool be useful, safe, and most importantly, reliable. The Maglite attachment provides police officers with an easy to use and versatile secondary light source. Our design is an attachment that will fit to an existing maglight, or similar flashlight interface.

MODULAR ATTACHMENT DESIGN:

The Maglite attachment can be modified to fit any full size Maglite base by removing the cap and threading the housing into the Maglite. The housing unit contains 2 puck lights that each have a rechargeable battery and 4 LED lights equally spaced around its circumference. Metal contact points on the bottom and tops of the pucks allow the pucks to be recharged by the D-cell batteries of the maglite through surface contact with the housing unit. This allows officers to purchase the attachment for use on their current maglite without any other modifications or charging stations for the pucks.

PUCK HOUSING/ EASE OF USE:

The housing unit for the pucks has a solid, lock tight feel. Its base is threaded identically to the caps that are already on maglites to allow quick transition to the attachment. The threaded design allows for the user to buy the housing to attach to their existing Maglite. The housing has a spring platform in its base that assists in dispensing of light pucks when the release mechanism is opened. The release mechanism incorporates 2 prongs that extend towards the center of the housing unit. When the textured grip is turned counter clock wise, the prongs are pulled back into the housing allowing one puck to be dispensed. The prongs are quickly returned to the closed position by turning the texture grip clockwise. This quick lock method allows for the pucks to be very quickly removed or reloaded back into the housing unit. The hard exterior of the housing unit is a continuation of the Maglite lite. This continuation maintains the rigidity of the Maglite and allows it to be used as a blunt force object, self-defense weapon, knock on doors, etc.

MULTIPLE LIGHTS-IN-ONE:

Police officers are often in situations in which they need lighting for searching small spaces or lighting up large areas. Large maglites provide difficultly in searching small spaces because of their length/bulk. Many police officers carry an additional "pen light" or smaller Maglite on their belts for scenarios like this. However, some police officers do not have the required space on their belt for a smaller light. The puck lights provide all the functions of this smaller light while still being integrated into the larger Maglite. This allows all police officers to have a secondary light source regardless of how much material they have on their belts. The small puck design also allows for use in a confined space and fit neatly within the housing. Finally, having multiple lights can serve as a beacon to guide backup police officers to the location of the first police officer. For example, if police officers enter an apartment complex, they could leave a light outside of the door that they entered to direct reinforcements to their position.

PUCK SURFACE ADHESION:

The pucks have several different methods to be adhered to different surfaces. One major adhesion method is a magnet integrated into the puck design. This magnet can be a hands free method for police officers to search a crime scene, perform a drug raid, or check documentation. Clips were also added to the back of the puck lights for police officers to attach the puck light to their uniforms. These clips serve as a safety precaution for police officers while performing a traffic stop if worn on their right shoulder; directing people's attention to police officer standing next to the car.

VARIABLE LIGHT FUNCTIONALITY:

The pucks have two different modes; constant light and strobe mode. The constant light mode is the primary use in situations such as traffic stops, drug searches, etc. with the strobe light as a secondary function. The pucks have one button; the first click turns on the constant light function, second click turns on the strobe mode, and the third click turns the light off. This function can be used in situations such as confined space entry to disorient anyone already in the confined space. It could also be used as a beacon because it easily grabs others' attention. The pucks also come in varying colors and intensities. All pucks have the same shape and design so a police officer could decide which pucks he wants to carry depending on the situation. In a situation where the police officer will be working out of his car, he can have a weaker red light to allow him to see his work while not dilating his pupils to the point where he can't see in the

dark at all. However, in a situation where a bright flood light is needed, the police officer can use a high intensity bright light to flood a crime scene or accident scene.

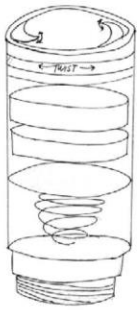
POTENTIAL MARKET:

After multiple visits to police substations, there is clearly a market for a product that will eliminate the need for police officers to carry multiple separate light sources. Police officers are responsible for purchasing their own equipment; however, every police officer has an inherent interest in having the latest and greatest technology. When questioned, police officers predicted that there would be a market if the housing and pucks could be sold for less than $30-40.

COMPONENTS:

Housing unit – The housing gives the attachment the feeling of a continuation of the Maglite. It allows for the user to maintain the same level of functionality as that of a regular Maglite (self-defense, knocking on doors, etc.)

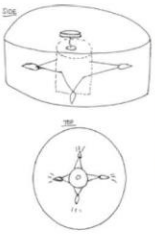
Twist Lock – Allows for the user to easily dispense one puck while only using one hand. It also provides a very secure method to hold the pucks while not in use. This design is extremely rugged and allows for the housing to be easily cleaned.



Threaded base – the threaded base provides a sturdy foundation to let the housing unit function as a continuation of the body of the Maglite. The threaded base attaches in place of the existing cap.

Spring Platform – the spring platform provides compression to the pucks lights to keep movement with the housing unit to a. minimum and assists in dispensing of pucks.

Rechargable LED Puck Lights – The puck lights are compact lights that can easily be used in confined spaces to light up a room during entry, or stick to metallic surfaces using the magnet attachment. The pucks also have rechargeable batteries that automatically recharge when returned to their housing on the back of the Maglite using metallic leads. The power source for the rechargeable batteries are the Maglite's D cell batteries.



Portable Bicycle Stand

Cycling enthusiasts use stands to tune and tweak their bicycles. Ideally, a good stand allows both bike wheels to be free from the ground. Currently, there are many different bicycle stands on the market. The biggest problem with all these stands is that there are few that can travel with the cyclists on a long ride (around 50 to 100 miles). Pictured below are several common bicycle stand designs.

Type A

Type B

Type C

From what is currently on the market, we saw three "types" of stands when it comes to functionality. Type A is non-portable and does not lift both tires off the ground at one time. Type B is non-portable but is capable of lifting both tires off the ground. Type C is portable, but again is not capable of lifting both tires off the ground for quick fixes. Our design is the ever-elusive Type D, in that it is both portable and capable of lifting the whole bike off the ground.

Our Product

Can be attached to any standard road sign

Our design incorporates two threaded 3/8"-16 studs that are spaced two inches apart. These studs are capable of fitting into the holes on a majority of street signs (see picture below). Simply insert these studs through the holes on a street sign and tighten the top wing nut to secure the base. Only one wing nut is needed, as the lower stud simply locates the bike and prevents twisting. The device can easily support the bike's weight. The bicycle can also be secured higher on the sign post so that the user does not have to strain their body when fixing the bike.

Fits all bike sizes

The groove cut into our product has a diameter of 1.5" fits all standard bike top tube sizes. The groove is lined with rubber padding for extra support, extra grip, and to prevent damaging the bicycle.

Extra storage for multitool(s), spare tubes, or anything else the modern cyclist needs

Along the bottom of the product, there is a 3.5”x2”x1.75” space for storage. This dimension is adequate for a large portion of multitools on the market today. To keep anything from coming out of this space while on a ride, there is a clear door that rotates over. This door is then secured by the straps.

Adjustable straps

The black straps secure the bicycle to the product. They have rubber lining where they would make contact with the bike frame for extra grip and damage protection. They also secure the door close for extra storage. In order to prevent the straps from sliding off of the product, there are angled grooves to keep the straps in line. The buckle allows for the straps to be tightened and remain tight until the user loosens them.

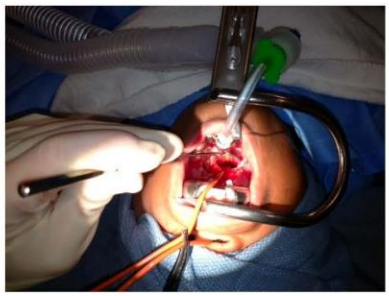
You won’t even know it’s there!

Out product has a very compact size that allows for any rider to take this with them on their long rides. The profile is slim so that it does not affect the rider’s cycling gait, standing or sitting. It can be attached in multiple places on the bicycle, but we found two places in particular that are the least noticeable (see figures). The product is also made of lightweight aluminum. This provides strength and rigidity, while not adding much more weight to bicycle.

Hands-free Adjustable Mirror (H.A.M)

Background

Our group shadowed the lead ears, nose and throat surgeon in the OR at Children's Nationwide hospital. We noticed several areas of the surgery that the procedure could be improved made easier with better equipment. The area we chose to focus on was the mirror used in most tonsil and adenoid removal. Currently the surgeon has to hold and focus the mirror with one hand and cut, or cauterize the tissue with the other hand.



Redesign

The current mirror was useful for suppress tissue and focus on areas of the throat that would have been impossible to see without it. However, the main drawback of the mirror is that it requires the surgeon to hold the mirror in the correct position for the duration of the procedure. This leaves the surgeon stranded with only one hand to perform the operations. The new design gives the surgeon both the flexibility of using the mirror at multiple angles as well as remaining stationary. The design also allows the user to use the mirror hands free, allowing the other hand to be used for other critical functions.

Hands Free Operation

The device mounts to existing Crowe Davis Mouth gag with three degrees of freedom. The clip allows the mirror to still be used manually if desired but when it is in the right position; it can be attached to the mouth gag for hands free operation.

Figure 1 Crowe Davis Mouth Gag

3 Degrees of Freedom Flexability

The redesign has three degrees of freedom, which allows it to rotate 360 degrees about the shaft axis. This is achieved by being able to rotate within the clip. The clip also allows for an adjustment of depth into the oral orifice, by allowing the mirror to slide up and down. The third degree of freedom comes from the angle adjustment on the mirror head. This is achieved with the spring and mechanism located at the top of the device. As the spring is compressed the mirror rotates up to roughly 90 degrees.

Additional Features

The final design will be made of stainless steel and a high temperature resistant rubber composite. This allows the device to be steam cleaned and reused in multiple independent procedures. However, the whole device can be manufactured and sold for under $50 dollars, this could also allow for the device to be one time use. The lock mechanism located on the grip holds the plunger and spring in place to keep the angle of the mirror stable.

Future Implementations

The rubber clip will be incorporated into a sleeve device that slips over the gag. The goal is to have the sleeve be disposable.

Morelock – Cable Service Box Security Device

Cable technicians travel to point of service and perform tasks necessary to establish service to customers. To control services, security is necessary at the junctions of the cable line to the apartment complex or home. Locks are necessary to deter tampering with equipment, i.e. theft of cable. Those locks are at present known as morlocks, and an example is shown below on the bottom of the junction box on the side of an apartment building.

These locks present myriad problems to the technician. To deter tampering, they have a recessed thread fastener that is actuated with a special tool when engages with a plunger actuated ball.

These are tools break easily, and are often broken as the holes fill will with dirt, ice, insect larvae, etc. and foul the tool on insertion. The alternative is to stand for long period with small pick tools, wire, etc. to clear the hole. This is a loss of time. The threaded fastener takes time to unscrew, and is often in a geometrically difficult place. Also, if there are bees in the box, that is time the technician would rather not take. It would be much better to simply key the lock open and stand back with bug spray, especially when the box is elevated and the technician is on a ladder.

Redesign Description

The device has been completely redesigned, in order to alleviate all of the problems experienced by professionals in the field. The new mechanism uses four slides that each move along a single axis in an enclosure, in conjunction with a locking pin that has four cuffs placed at equal intervals. Each of the four slides has a circular hole (of the same diameter as the locking pin cuffs) somewhere on the axis along which it travels. When the four slides are moved such that the four holes are aligned, the locking pin will move freely. The slides protrude from the enclosure, allowing all four to be pushed inward by a special

tool, calibrated to the four values of Δx that will align the holes and allow the pin to be removed, and thereby unlocking the mechanism. A small sheet of pliant material behind the slides acts as a spring, applying force in the direction opposite to that of the tool so as to keep the slides in position when the lock is in place.

Removing Potential for Obstructions

Central to the redesign was the desire to limit or eliminate all recesses in the mechanism when in use. This prevents obstructions like dirt, ice, and insects from becoming lodged in the mechanism, allowing for quick removal and access to the cable service box.

Speeding Up Operation

By developing a device that doesn't require the threading and unthreading of a bolt, the operation of unlocking the mechanism is sped up dramatically, and the simple nature of the tool allows for easy one-handed operation. When the lock is to be reapplied, the locking pin is simply pushed past the slides and into place

Creating a More Reliable Tool

The tool itself is incredibly simple and reliable, having no moving parts and being precisely machined to open a specific subset of the newly redesigned lock.

Maintaining and Increasing Security

With the existing Morelock design, a would-be cable thief could simply look inside the recess and it is apparent how the lock functions. Though the action of pushing in the four slides is almost immediately evident, with the redesigned mechanism, the distance of travel required by each individual slide is impossible to know while looking at the lock, and very difficult to replicate without the specially calibrated tool, making the design reliably tamper-resistant.

Providing Compatibility for Transitional Period

Double-ended tool with one end being the existing Morelock ball bearing design provides compatibility with existing locking mechanism until, ideally, they are all replaced by the new design.

An Alternate Medication Dispensing System

The average elderly American takes 5 or more medications a day and deals with an array of physical and mental barriers to the proper administration of those medications. Arthritis, weakness, and a general lack of mobility (both within the home and without) can prevent a patient from accessing the medication they need, while cognitive impairment can cause them to skip a scheduled dose or inadvertently overdose from taking the wrong medication or forgetting they've already taken one. Studies show significant percentages of patients experience an adverse reaction to drugs in their lives due to these reasons. In addition, while caregivers such as nurses and family members do not suffer from these conditions they are limited in the time and effort they can devote to the organization and delivery of medications and ensuring that their patients are adhering to the proper schedule.

Redesign:

In order to resolve these issues we must address the physical and cognitive loads placed on the patients and the temporal and difficulty loads on caregivers. To that end, we have designed a solution that automates much of the organizing, scheduling, and dispensing of medication and streamlines the entire process from pharmacist to patient dosing.

Wristband

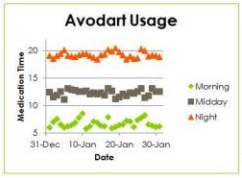
One of the key aspects of this product is that it is always with you. This sleek wristband is very simple and noninvasive; it allows users to go about their daily lives until reminding them that it is time to take their medication. The main device sends a signal to the wristband when it is time to take the medication; upon receiving the signal the wristband vibrates and lights up to indicate to the user to go to the dispenser. The user then has to option to go to the dispenser or to press "snooze"; the snooze function will only work as long as the user is within a safe time range to take the medication. Once at the medication dispenser, the user swipes their wristband to distribute the necessary medications. This is to ensure that no unintended users get ahold of any potentially harmful medications.

Main Dispensing System

The key to this design is the hopper system to hold and organize the medications. Once the various medications are received from the pharmacist, the user scans the QR code using the scanner and the proper hopper lights up indicating to fill that hopper with the scanned medication. After filling the hopper, the pill bottle from that medication is then placed in the holder in front of the hopper in order to provide further visual reference for the user. The clear hopper design allows the user to see the medication and the amount left. If the medication is running low the hopper lights up red; indicating for the user to go refill their prescription.

The user and doctor determine the optimal schedule ahead of time. This schedule is put into the QR code which gets read by the machine. The user is give the option to hit the "snooze" button if the medication is able to be taken in a certain time range. For medications that are not on a particular schedule there is a "take as needed" function. In order to receive one of these types of medications the user would press the hopper for that particular medication and one dose would be dispensed. If the medication had already been taken the maximum amount of times that day or if the user request the medication too soon after taking their last dose, the device will indicate that to the user. The user then has the option to override the warning and receive the dose anyways.

Doctor/Pharmacist Communication



Average Per Day	3.16 Pills
Days over recommended amount	3
Average Time Between Doses	5.2 Hours

Currently when patients need a refill of their prescription medications they need to notice their medication is low, make sure they still have a valid prescription and/or refills, call the pharmacist to tell them that they need a refill, and then pick up the medication from the pharmacy. Under our redesigned system, patients will scan the pill bottle when it is first acquired from the pharmacy. The machine will then be able to keep track of how many pills are left and when a refill is needed. When the patient is running low they can either have the system automatically reorder the pills or the system can remind the patient to reorder them (this is a preference set by the user). The machine will also give a warning if the prescription is going to expire soon. In this way there is less of a chance that the patient needs a medication but is not able to due to forgetting to get a refill.

The only way a doctor knows their patients' medication comfort level and/or usage patterns is through what the patient tells the doctor. Under our new system, the machine will automatically send a doctor the data and a graph of when the patient is using the drugs. In this way, the doctor will know if the patient is following his usage time instructions and can adjust the recommended schedule based on what the patient is doing. For use as needed drugs, seeing the patient usage patterns will allow the doctor to know if a stronger or weaker drug is needed.

Police Radio Handset

One of the most important tools a police officer uses on a daily basis is his radio. Typically, an officer carries a large radio on his belt, a handset on his shoulder, and a radio handset connected to a radio in their car. This creates an unnecessary amount of tools. In addition, one of the biggest problems with current police radio headsets is the push to talk feature. An officer is required to push a button on the side of the handset to communicate, which is extremely undesirable in a variety of common situations. When an officer is in pursuit he typically is required to call out the street names of each turn he is making. In this time of immense danger and required concentration the officer ends up driving with a single hand as the other tends to be fully occupied by the radio. This is also undesirable since an officer will likely need a free hand during other situations such apprehension of a suspect, another instance where constant radio communication is of essence. Another problem with the current headset is the shear amount of buttons and redundant controls on the handset, many of which the officer does not know how to use or even what the buttons function is. In fact, an officer rarely uses more than three stations.

Redesign:

We chose to redesign the police radio handset because, in doing so, we were able to make the handset easier to use for police officers and eliminate redundant equipment and features. The overall shape and the location of each feature were also designed to optimally fit the users' hand.

Push to Talk

Currently, officers need to press a button located on the side of the handset. This is difficult to find and then an annoyance to keep held. We relocated the talk button the front of the handset and made it large so that it is easy to find. The push to talk feature has three modes so that the officer can use the one that is most convenient for a particular situation.

1. Quick Push – This will be the preferred method. The officer can quickly press the large button and the handset will be on until the officer's voice ends. This is extremely convenient while driving or for normal conversations when the officer doesn't want to keep his hand on the handset the entire time he is speaking.
2. Press-and-hold – This will be used in noisier situations when the handset cannot determine when the officer stops speaking and when the officer has a short message. He can simply hold the push-to-talk button down until his quick message is over.
3. Pull lever – the button also has a lever mechanism that can be pulled. This will let the officer speak until he returns the lever. This is used in noisy situations where the handset cannot determine when the officer stops speaking, and the officer has a lot of information to convey over the radio.

Preset Buttons

Three preset buttons were placed at the top of the handset. These can be set by pressing and holding the buttons while a current channel has been selected by the main radio. This eliminates the redundancy of all the buttons and allows an officer to quickly switch between the 1-3 channels he typically uses.

Volume Control

Rather than having knobs at the top of the handset like current models, a scroll wheel was added to the side of the handset. This allows the officer to quickly adjust volume without having to look at the handset to locate the control. The scroll wheel was placed at a position where a typical thumb would rest.

Larger Speaker

The speaker size was increased and placed in a position where the officer's hand would not block the sound. This allows for a much clearer signal coming through the handset.

Panic Button Relocation and Safety

The panic button was relocated from the front of the handset where it could easily be pressed to the side of the handset below where a typical thumb would rest. This ensures the officer will only press it when he means to. In order to further protect accidental presses, the sides around the button were raised. These also help the officer find the button quickly if needed.

Easy-to-attach clip

On the back of the handset a clip was placed that can be easily attached to most clothing or straps. This allows the officer to place the handset in a location most convenient for him/her.

Spent Grain Press

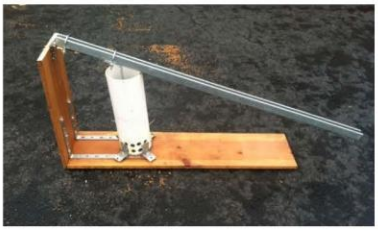
During the beer brewing process, a large amount of grains get removed from the mash tun, and is typically disposed of with no benefit to the brewer. However, Elevator Brewing Company wanted to find a use for this waste that would be a net benefit to the company. Elevator Brewing is also planning on installing in-floor heating soon that will utilize a wood burning furnace to heat the water flowing through the floors. This provides a natural opportunity to utilize the spent grains as fuel for the furnace. However, before the grains can be burnt, they need to as much excess water removed from them as possible.

Constraints

Elevator Brewing provided a unique challenge with some very specific constraints. First, the method of dehydrating these spent grains could not be expensive in terms of time, money, or electricity. Any employee that had to spend time working with the spent grains was removed from the actual beer making/bottling process and would lead to an overall decrease in efficiency. Currently, the spent grains as waste do not cost the brewery a noticeable amount of money to get rid of, so any design would need to not add a cost to the brewery at the end of the day. In the near future, in-floor heating is being added to help decrease the cost of heating the building, so any electricity used on the grain dehydration process would be counterproductive. Additionally, space in the brewery can be limited when there are high volumes of beer waiting to be shipped, so size has to be a concern. Lastly, if the spent grains remain unused for a 24-48 hours they start to rot and have a strong odor.

Initial Design Ideas

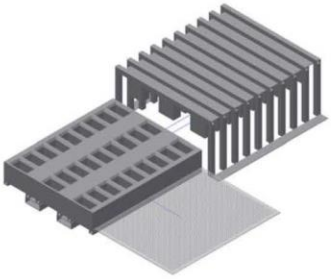
Initially a wide variety of dehydration methods were discussed. Ideas varied among using direct pressure, air drying, rotating grinders, and dehydration machines. Direct pressure using different mechanical advantages provided a solution for most of our constraints, but not all of them. The direct pressure model required either electricity to operate or it required an employee's attention and effort. The air drying method did provide a passive method of processing the grains, but space limitations and very foul odor make this this design unrealistic for this application. The rotating grinder ideas had the same limitations as the direct pressure methods, with the added challenge of increased complexity. Dehydrations machines possibly had the most potential for drying the grains, but as with air drying, space and odor where major concerns, along with the addition of electricity. In the end, the direct pressure method was our best option for this project.



Final Design

Our design uses the power of a forklift to press, and therefore, dry the grains to be used as a source of fuel. By using a forklift, which Elevator currently owns, the design will not require a large up-front cost and/or additional electricity. The press can compact large amounts of grain in a small amount of time allowing two employees to finish the job quickly. Currently, the employees must fill barrels with the grain while emptying the mash tun, therefore the new design will add a minimal amount of time to the job. Previously the grains would start to smell after only a few hours in the barrels, but with the new design the grains will be taken care of immediately after use. Our design also takes up a minimal amount of space and does not need to be moved within the building, which is critical, due to the space constraint within the brewery.

Our design consists of three parts: the fixed upper frame, which is mounted to the floor, the lower portion, which is driven by the fork lift, and a thick removable plexiglas plate, used as a strainer/screen. The fixed upper frame contains rows and columns of positive inserts which line up with the lower voids. The lower portion, driven by the forklift, contains voids which are filled with grain and then driven under the fixed frame and upward, pressing the positive inserts on the frame into the voids.



Dental Mirror and Rheostat

Dental mirrors are one of the most frequently used tools in the dental office. Dental hygienists as well as dentists use them repeatedly on a daily basis. Typically dental mirrors are stainless steel for cleanliness and small for ease of use in the user's hand and in the patient's mouth. The issue with the current mirror is that the mirrors visibility is obstructed by a variety of things such as water, debris, and fog. This forces the dentist or hygienist to stop what they are doing to clean the mirror. Having to stop an operation or procedure to manually clean the mirror can be detrimental to the procedure, distracting for the user, and cause the procedure to take longer. The most common time that the dentist has to clean the mirror is when they are using the dental drill. The drill sprays water which usually accumulates on the mirror in combination with the tooth debris. This causes the user to have to clean the mirror frequently.

Redesign:

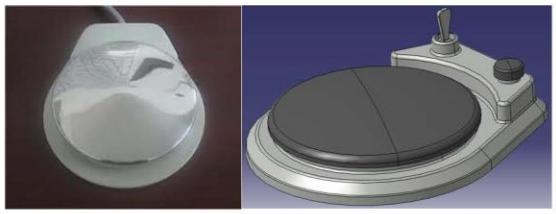
After talking with a few dental students, our group decided to redesign the dental mirror to try and prevent obstructions from rendering the mirror useless and to decrease the time it takes to perform the procedure. While in the process of redesigning the mirror it was determined that the pedal had to be redesigned to accommodate for the modifications and new capabilities of the mirror. The redesigned focused on the dentists as the major users because they are the users that use the drill and mirror together. The redesign can also be used by the hygienist.

Debris Removal System

A flow of air is directed over the surface of the mirror to clear the obstructions off of the mirror and removes fog. A small orifice near the attachment between the handle and the mirror allows air to be directed across the mirror surface. This design allows for the mirror handle to be approximately the same thickness so the feel in the hand for the user is only slightly different. The mirror when in use will be attached to a small diameter air line to minimize weight and restriction of movement. Another way feedback is removed is by adding a rotary joint and spring at the connection of the air line and mirror so that it is easier for the user to articulate the mirror without being constrained by the hose. Users will also be able to select whether they would like the mirror to start flowing air at the same time as the drill being turned on or they can turn the flow to the mirror off while drilling.

Hands Free Mode Selection

The users of the mirror use the mirror in all different orientations. In order to prevent the user from having to change the orientation to activate the cleaning of the mirror the mode selection capability was moved to the pedal instead of the mirror itself. The placement of the actuating system on the pedal frees the user to continue using the mirror as they need, still have the ability to switch between the modes of use, and allows the mirror to be very similar to the current weight and feel. The location of the button to turn the air flow on and off to the mirror allows the user to be able to enable and disable the button without needing to look down at the pedal. One mode will be an automatic mode that turns the flow of the air to the mirror on at the same time as the drill being turned on. The other mode will turn the air flow to the mirror off while still being able to utilize the features of the drill.



Quick Disconnect

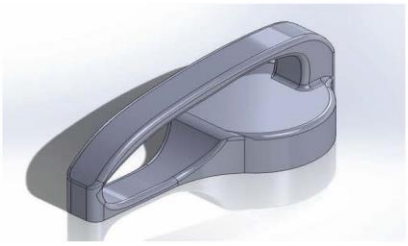
Due to the rotary joint and the need for quick and easy connectivity between the mirror and the air line, a docking port was developed to secure the rotary join to allow for a quick disconnect while only using one hand to do so. The port that secures the joint to disconnect the mirror from the hose is located on the table that holds all the air tools. In order to disconnect the mirror and hose, the assembly is placed into the cradle and then turned to disconnect the two; reassembly is the opposite order of operations. The purpose for the quick disconnect is to allow for the mirror to be used as a traditional mirror, save time connecting the mirror up to air, and be immediately ready for use to clear obstructions off of the mirror surface.

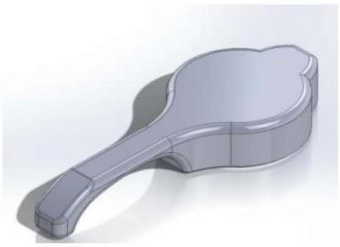
Simplified Dog Leash

The dog leash is device commonly used by nearly all dog owners. These owners range from the everyday dog owner to the extreme dog owner (i.e. K-9 unit officers, search and rescue dogs, etc.). Leashes can be as simple as the loose line leash as seen above to the left. A major issue with the loose line leash is that they can easily become tangled if not stored properly. An existing improvement to the loose line design can be seen above on the right where the line of the leash is retracted into a cartridge; this prevents it from getting tangled. Even though it prevents tangle the cartridge can be bulky and cumbersome. The main focus of our design was to create a leash that was compact, lightweight, attachable, lends itself to easy storage, and remained tangle free.

Redesign

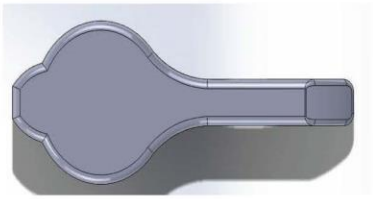
We chose to take the retractable leash design and integrate it into a harness/collar setup. To do this we had to redesign the geometry of the handle so that it could best fit with the harness or collar. A method for allowing the handle and retracted leash to rest upon the dog while not in use also had to be design. The solution we arrived at was to design a leash that would retract and lay parallel to the top of the dogs back. The handle stays in place by magnetically attaching to the dog's harness. The handle is also anchored to the harness at one point; this anchor can be undone if one desires to remove the leash from their pet. While designing this new leashing system it was important to consider how the leashing system felt for dog and also how to make it very user friendly.





Handle Geometry

The key part of designing the handle was coming up with a geometry that would allow it to be small and comfortable to its users while retaining the required functionality. If there was a large handle resting on the dog's back or neck it could become obtrusive and possibly dangerous for the dog to wear. Although, the smaller the handle the better for this design, it also had to remain large enough for the owner to easily grasp when they wanted to control their dog. We decided to design a handle that one would hold in a similar fashion of holding a flashlight. The handle extends off of a circular housing that contains the leash and a tightly wound flat metal spring that retracts the leash. This allows the leash and handle to lay flush against the dog's back.



Leash-Handle & Harness/Collar Integration

The main aspect of this leash that makes it stand out from other leashes is its integration with the dog's harness or collar. The leash and handle retract and connect to the dog's harness/collar; this allows the owner to leave the leash on their dog following a walk. This feature gives the owner freedom from having to connect and disconnect the leash several times a day. However, they still can remove the leash if they so desire by un-anchoring it from the harness. The most appealing aspect of this feature is how quickly a owner can gain control of their pet; then conversely give their pet their freedom back by simply placing the leash onto their back.

Sports Bag

Sports bags are used by nearly all sports that require the use of equipment. Bags such as the pair above (hockey bag on the left, regular gym bag on the right) provide a simple and organized way to get gear to and from the sporting event. With current bags, there are two major issues encountered by recreational athletes. First off, since there is often lots of padding and absorptive fabric in equipment, a lot of a player's sweat is absorbed by their gear during use. For equipment to dry properly and to keep it from getting smelly and infested with harmful bacteria and fungus, it is necessary to lay out the gear immediately to let it air out. Unfortunately, for many recreational athletes this is not an option, as they do other things such as getting food, meeting with friends, etc. after sporting events. Secondly, when it is time to lay the equipment out to dry, many athletes simply do not have anywhere to sprawl their equipment out, particularly those that live in dorms or small apartments.

Redesign

In order to redesign a sports bag to tackle these problems, it was important to work on three key aspects of the bag. First, it was important to consider the material the bag was being made of. Many current bags are made of vinyl, which is non-porous material that does not allow moisture to escape the bag, keeping equipment wet. Secondly a form of active drying was determined to be the best way to aid in combatting wetness during the period in between the end of the sporting event and when an athlete got home. Finally, an organizational aspect needed to be included to give those without too much extra space a way to continue allowing their equipment to dry.

Material

A mesh material was chosen to give maximum breathability to the bag. Supportive, stronger fabric was used to create the framework for the bag and bendable metal dowels were inserted through the supportive fabric to add some structural integrity. The entire framework was sown together.

Active Drying

For the version of the bag modeled here (a small gym bag, in this case being used for soccer equipment), two 200mm fans were attached on either end of the bag. With the mesh body and fans of this size, good airflow could be achieved over the contents of the bag, allowing for some active drying to take place immediately. In a true prototype, the fans would be covered with farily heavy duty grills and be in strong casing to prevent them from being damaged by or damaging the equipment. They would run on a rechargable battery that could be plugged in one the athlete got home.

Organization

In order to create a simple way to air out equipment without taking too much space, a radically different design was created. Instead of having a top zipper in the bag, the bag was separated into a series of pockets. The fan end caps would be attached via zippers (for ease of implementation, Velcro was used on the prototype) on both ends and could thus be opened to allow one to place equipment in the individual pouches. Once at home the athlete could unzip both sides, allowing the bag to unroll, and could then hang the unrolled bag by the loop at the top. This could be done in a closet, on a door, or any other area where there was space, giving the equipment a way to air out without having it laid out on the floor or even taking it out of the bag.

The Teacher

The most fundamental element of learning according to the teacher we shadowed is time with the students, teaching them through explanation and demonstration. But many aspects of the teacher's job detract from this time, such as the time required to individually testing students, analyze test results, or review student's work during the day. These tasks, while worthwhile, detract so much that they rarely get done if at all.

The Design

The design to the solution to this problem is a student tablet computer. This is not meant to supplement the teacher but to handoff number crunching and administrative tasks to computer, which in turn gives the teacher more time to interact with the students and give access to powerful analytics that greatly increase the teaching effectiveness and efficiency.

Workstation with mobility of a tablet

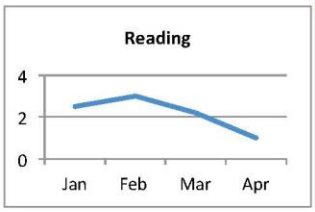
The student tablet functions not only as an actual table, but a workstation as well. This will replace the need for desktop computers in the class room and computer labs. The tablet itself can used in three setups. The first is the workstation, where the keyboard is out and the screen is propped up by the folded back cover. The keyboard can then be folded back for the touchscreen workstation. When the cover and the keyboard are both folded back the device can be used as a tablet when on the move or just as a piece of paper would, where the user can choose for the screen to only respond to the stylus.

Everything in one

The device is meant to replace the stack of book and materials a student must carry from class to class. The tablet itself functions as the text book, assignments, notes, calculator, and everything else a student may need for class. In addition the inside of the cover also serves to carry miscellaneous items, and has a pocket for papers that just can be digitized, such as permission slips. The outside of the cover also has a mesh pocket to carry large items in.

Analytics

The most advantageous ability of this device is the real time feedback from students and automated analytics. This gives the ability to correct a student's work immediately, rather than the next day after the assignment has been graded by hand. In addition the teacher can break down the grades and get itemized results to find weakness in the class and individual students.



IV POLE DESIGN

IV poles are vital tools used in hospitals worldwide by health care professionals, patients and their caregivers. For our project, we shadowed a nurse from University Hospital East, ICU. From our visit, we learned that the main purpose of the IV pole is to support heavy IV pumps and IV bags for the patients. Issues with the current IV pole design are: (1) it is difficult to use the current screw clamp to attach the IV pumps to the poles, (2) the stability of the pole when pushed along, possibly loaded with 6 total IV pumps using 2 IV poles, and (3) the plugs from the individual pumps can become tangled and confusing.

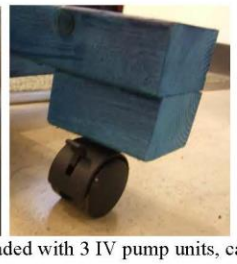
Redesign:

We chose to redesign the IV pole because there are many shortcomings with the current design that can be solved to boost the mobility, stability, ergonomics of the pole, as well as the efficiency of the user.

Mobility:

Currently, the IV poles could be loaded with 3 IV pump units, requiring 3 plugs that all need power from the wall outlet. Our redesigned pole features a battery power source that is attached to the bottom of the pole. The IV pump units can be plugged into this single power source unit which has a singular power cord that gets plugged into the wall. This plug is also retractable with the push of a foot pedal. This solves the issue of the nurse having to unplug and manage the 3 separate cords when transporting a patient. For moving patients on their beds, our pole will be attachable with a rigid coupler link that will mount onto current backsides of beds. The clamp for this connection is the current screw clamp to allow compatibility. This coupler link will fix the pole to the bed, which will follow the bed through transport of the patient to various rooms without worry. This is a task that used to take 3 people to transfer a patient from one room to another. A hospital should keep X amount of these couplers in their supply room, and the nurses should retrieve one when necessary.

Stability:



Currently the IV pole, loaded with 3 IV pump units, can become top heavy and has the chance to be tipped over, most likely resulting in injury.

We solved this with the addition of the battery power source at the base of the pole. This allows the majority of the weight to be distributed at a stable location which lowers the center of gravity of the pole making it harder to tip over. In addition to having the battery as a part of the pole's base, future models of the IV pumps can be improved. The majority of the

weight in a pump comes from the battery which can now be reduced in size due to the battery relocation. Also, to improve stability, our redesigned pole has locking wheels to prevent unintentional movement, similar to a baby stroller.
The use of the rigid coupler link increases stability of pole when transporting patients. The same coupler can also be used to fix the IV pole to a rigid pole mounted on the room's wall, also preventing tipping.

Efficiency

Since our design has a combined power supply for all the pumps, it is quicker for the nurse to set up and move. When a patient needs to be transported a nurse simply unplugs the single cord from the wall and retracts the cord into the power supply. This reduces the time spent managing multiple cords.

The IV pumps are stand-alone units that must be attached to the IV pole. The current system is a screw-type clamp that tightens against the pole. To properly use the screw clamp it must initially be open enough to clear the pole. Then the pump must be supported with one hand while the clamp handle is turned until tight. Our design uses a spring-loaded pin through holes in the pole. The holes are located every 3" with a groove through them to align the pin. To attach units to the pole the user simply retracts the pin and lifts the pole to the desired height then releases the pin into a hole. Our design always defaults to a ready to use position, it is faster to attach, and requires less force from the user. In addition to making this process more efficient for the nurse, it saves them considerable effort by reducing the time they must spend holding the IV pump which is deceptively heavy.

Ergonomics

The IV Bags must be held high above the patient and pumps. The current design has the bag holders at a fixed height at the top of the pole, which can be difficult to reach for shorter nurses. Our design has an adjustable height bag holder; the nurse can lower the holder to attach the bags then raise it to the proper height, or simply leave it at a lower height if that's suitable.

To increase the ease of maneuverability, a comfortable adjustable grip was added to the pole. The vertical orientation of the handle should reduce the tendency of some patients to lean heavily on some parts of IV poles which creates tipping problems. The handle height is also adjustable to accommodate different sized patients.

First Responder Kit

Background

Emergency personnel respond to a wide variety health conditions and life-threatening situations; since the medical equipment required is different each call, an array of the most frequently used emergency equipment must always accompany them to the scene.

This is the first responder kit.

Redesign:

The primary goals of our redesign were to make the kit easy to carry and to allow it to be used while in the back of the ambulance.

Hands-free Toting

A first responder kit is currently a hard-case box with handles on two adjacent sides. Since the emergency responders must have their hands free in order to transport the gurney, they often place the kit on top of the gurney while moving to the scene, where it must be removed to accommodate the patient. The kit must then be carried back to the ambulance while also moving the loaded gurney.

Incorporating shoulder straps allows the user to transport the kit "book-bag" style, freeing both arms and hands to more easily move the gurney, which is not an easy task. In conjunction with shoulder straps, the use of contoured padding will result in a much more comfortable interface than the current metal casing.

The redesigned kit will be molded from a rigid polymer with strength and weight considerations in mind. This will protect the contents from the hazards presented by potentially dangerous environments. Inside the kit, dividers allow for easy organization and quick distinction between critical medical supplies.

Anchoring and Organization

Once the patient is moved into the box, the emergency kit is put away, and identical medical supplies available in the box are used to address any concerns that were not addressed at the scene. This redundancy confers no benefit to the user or the patient. Furthermore, it is usually the case that supplies must be passed from a responder in a "jump chair" at the head of the patient to the primary caregiver who sits on a bench beside the patient.

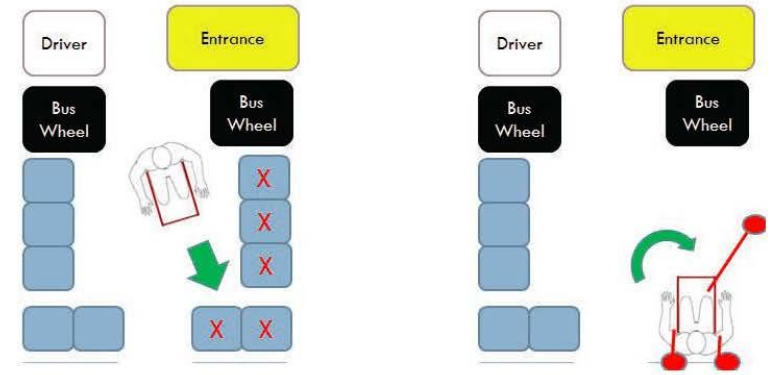
The redesigned kit can be quickly mounted (via magnets) onto the bench next to the primary caregiver, becoming a personal workstation with all the most frequently used supplies readily available. This would allow the kit to act as both a table and storage area as the ambulance drives to its destination. It also shortens the time required to perform basic care by eliminating the need for the primary caregiver to ask the responder in the jump chair to pass over needed medical supplies. Finally, this eliminates the need for redundant medical supply inventory that adds no value.

Flexibility and Future Development

As with the current setup, the first responder kit could be customized to fit a particular department's specific needs. Specified interiors (potentially exterior shell designs as well) could satisfy extreme user needs/demands. A direction of future development for this kit is to use a "smart system" by which departments can easily track the inventory of medical supplies as they are used on various calls. Tracking which items are used would allow the responders to make sure that everything that is used gets replaced, and reduces how much inventory the department and hospital must keep on hand.

Bus Wheelchair Restraint By: [redacted]

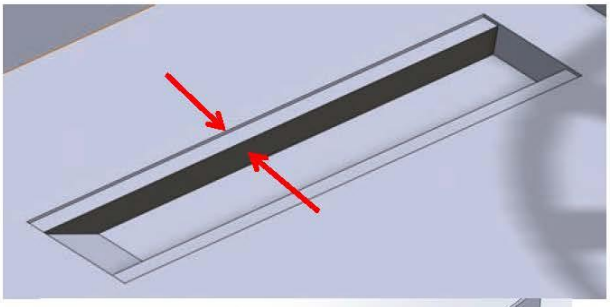
Many individuals reliant on wheelchairs depend on public transportation in their daily lifestyle. The current method of transporting travelers in a wheelchair requires an involved and lengthy preparation process. Upon entering a bus, the traveler must roll their chair through the tight aisle and make several hairpin turns and back into position. The bus driver must move up to 6 regular seats then begin the tiresome task of positioning the chair, assessing a way to tie down the chair and proceeding to strap the chair in place before continuing with her standard driving duties. This process is undesirable for the driver and the traveler. The tie-down process has been observed to take 3-5 minutes or longer (10 – 15 times the length of an average stop) which delays the bus and passengers. Due to the complication and variation in the process, more often than not the chair is not tied down following the recommended standards and therefore safety becomes a concern. The traveler is dependent on the driver to secure and prepare for the trip. After helping get the chair into position, the driver must reach under, around and over the traveler grabbing straps then finding a place to attach. Meanwhile, the traveler is sitting in the chair waiting for the whole process to be over. Imagine going through this process, then the reversal of the process at your stop 10 minutes later, repeating the entire process when you transfer buses and finally repeating the entire process on your return trip home.

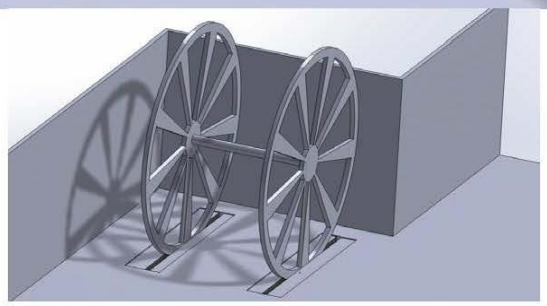


Redesign

Designing an automatic restraint returns independence to the traveler. The bus driver simply verifies a secure restraint and proceeds with the route. Auto-placement removes the option to incorrectly, and unsafely, restrains the chair. In addition, the new design adds ergonomic improvements such as a headrest and accident friendly seating position.

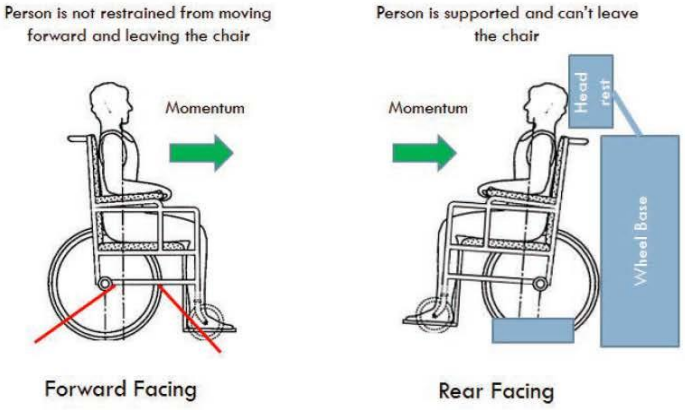
Replacing straps are grooves in the floor that compress the wheels of the chair securing it in place. The process is activated by the traveler via push-button with the necessary sensors and fail-safes.





Ergonomics

Research shows that a rearward facing position provides better protection in the result of an accident. A headrest was added as an additional safety and comfort.



Appendix G: Informed Consent Form

The Ohio State University Consent to Participate in Research

Study Title: The Educational Impacts of a Design Constraint Matrix
Researcher: Blaine W. Lilly

This is a consent form for research participation. It contains important information about this study and what to expect if you decide to participate.

Your participation is voluntary.
Please consider the information carefully. Feel free to ask questions before making your decision whether or not to participate. If you decide to participate, you will be asked to sign this form and will receive a copy of the form.

Purpose, Procedures, Risks and Benefits:
This experiment is intended to examine the effectiveness of using a design constraint matrix in an engineering design education context. Participation in this study will occur over the course of five weeks, as part of the second lab project in ME 65682/ISE 5560. After your class is randomly assigned to a test or control group, you may be provided with a constraint matrix tool, and instruction on its usage. Throughout the remainder of the study you will be asked submit surveys and journal responses intended to capture information about your understanding of the design problem, your own learning process, and your group's interaction with respect to the design problem.

After the semester is over, and your grades are submitted, the design outcomes will be evaluated by design experts in order to assess the impact of the constraint matrix. There will be no identifiers associated with any design outcome, and this process will be completely anonymous.

There are no foreseeable risks or discomforts associated with participation in this study. Participation in this research will potentially benefit your understanding of the engineering design process, and the management of the many factors which contribute to successful design outcomes. Additionally, this study is of general pedagogical benefit because it will help design educators to better understand how engineering design students cognitively manage the multiple factors which comprise a real-world design problem.

Your participation is voluntary. Refusal to participate will involve no penalty or loss of benefits to which you would otherwise be entitled, nor will it influence your grade for this course in any way. If you choose not to participate you will be provided with an alternative that represents an approximately equal amount of work. You are free to withdraw consent at any time and to discontinue participation in the study without prejudice.

Duration:
You may leave the study at any time. If you decide to stop participating in the study, there will be no penalty to you, and you will not lose any benefits to which you are otherwise entitled. Your decision will not affect your grade, education, or instruction within ME 5682/ISE 5560.

Confidentiality:
Efforts will be made to keep your study-related information confidential. Although data collected from this experiment may be made available to other researchers, your data will not be personally identifiable. However, there may be circumstances where this information must be released. For example, personal information regarding your participation in this study may be disclosed if required by state law. Also, your records may be reviewed by the following groups (as applicable to the research):

- Office for Human Research Protections or other federal, state, or international regulatory agencies;
- The Ohio State University Institutional Review Board or Office of Responsible Research Practices;

Participant Rights:
You may refuse to participate in this study without penalty or loss of benefits to which you are otherwise entitled. If you are a student or employee at Ohio State, your decision will not affect your grades or employment status, nor will it affect the grades of your classmates. If any member of a group has opted out of the study, the group's design outcomes will be removed from the study and will not be evaluated.

If you choose to participate in the study, you may discontinue participation at any time without penalty or loss of benefits. By signing this form, you do not give up any personal legal rights you may have as a participant in this study.

An Institutional Review Board responsible for human subjects research at The Ohio State University reviewed this research project and found it to be acceptable, according to applicable state and federal regulations and University policies designed to protect the rights and welfare of participants in research.

Contacts and Questions:
For questions, concerns, or complaints about the study you may contact **Blaine W. Lilly,** 201 West 19th Ave., Room 350, Columbus, OH 43210, 614-292-2297. Or, Paul Scudieri 330-219-2026.

For questions about your rights as a participant in this study or to discuss other study-related concerns or complaints with someone who is not part of the research team, you may contact **Ms. Sandra Meadows in the Office of Responsible Research Practices at 1-800-678-6251.**

Signing the consent form
I have read (or someone has read to me) this form and I am aware that I am being asked to participate in a research study. I have had the opportunity to ask questions and have had them answered to my satisfaction. I voluntarily agree to participate in this study.

I am not giving up any legal rights by signing this form. I will be given a copy of this form.

Printed name of subject	Signature of subject

	AM/PM Date and time
Printed name of person authorized to consent for subject (when applicable)	Signature of person authorized to consent for subject (when applicable)
Relationship to the subject	AM/PM Date and time

Investigator/Research Staff

I have explained the research to the participant or his/her representative before requesting the signature(s) above. There are no blanks in this document. A copy of this form has been given to the participant or his/her representative.

Printed name of person obtaining consent	Signature of person obtaining consent
	AM/PM Date and time

Appendix H: Evaluator Survey

Instructions for Evaluation of student design projects:

Each of the included design summaries represents the result of a seven-week design process, conducted as a part of an engineering product design course at the Ohio State University (Mech. Eng. 5682). Each project was completed by a team of 3-4 engineers from a variety of disciplines.

For the project, students were asked to choose a user group, and conduct in context observation of the users performing some task. After interacting with users in their context, the students identified a problem or opportunity that they could solve. The final deliverable for the project was a prototype intended to capture and communicate their design ideas. These prototypes are not fully functional. If this were a real-world design process, a considerable amount of development, design, and engineering would remain in order to bring these ideas to market.

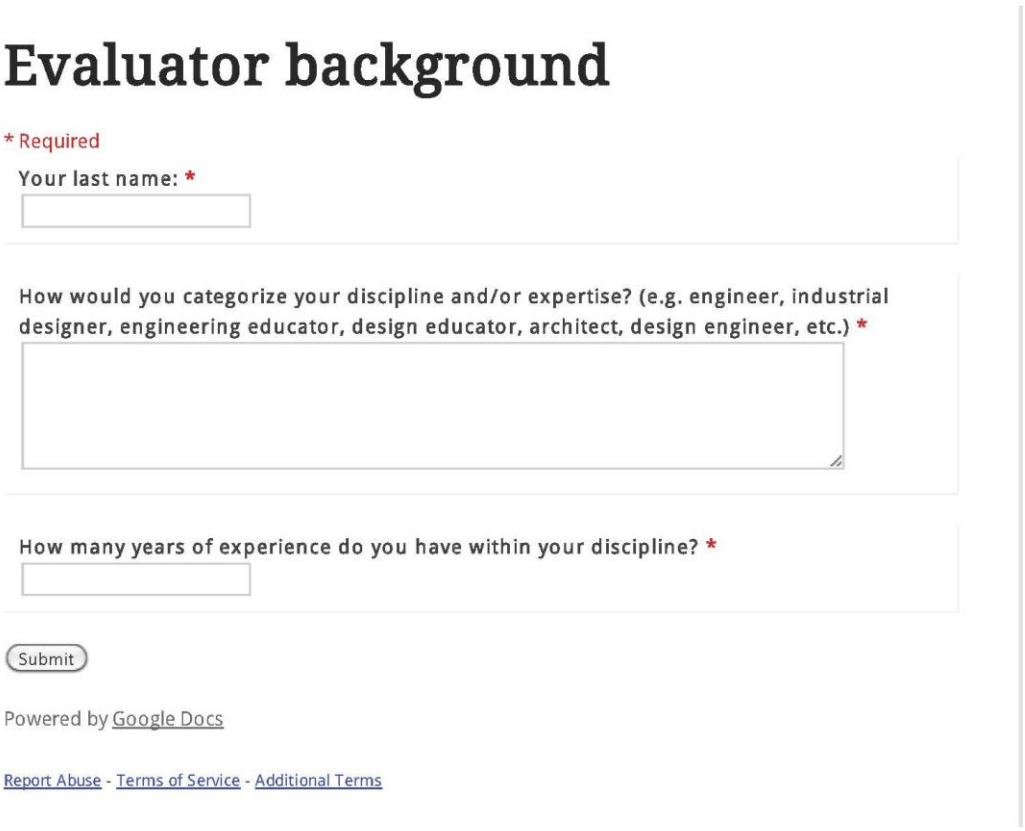
For a large majority of the students, this class represented their first experience with human-centric design, design for manufacturing, and prototyping. As such, I ask you to evaluate these designs with this in mind. Please focus on the ideas and concepts more than the presentation, quality of prototype, etc.

Prior to reading each summary you can click the link on the preceeding page, which will take you to an online form at which you can complete the evaluation of that design. It is important that you include your last name and the project number on each score sheet. Please note that the projects will be in random, rather than numeric, order. So make sure that you enter the correct project number. As each score sheet is submitted independently, you can complete these evaluations at your own pace, picking up wherever you left off. On each evaluation, there is a space for detailed comments, but the numerical evaluations are all that is required. Do not feel obligated to comment.

Before beginning the evaluations, please answer a few questions about your own background: Google Form: Evaluator Background

I truly appreciate your help.

-Paul Scudieri



Evaluator background

* Required

Your last name: *

How would you categorize your discipline and/or expertise? (e.g. engineer, industrial designer, engineering educator, design educator, architect, design engineer, etc.) *

How many years of experience do you have within your discipline? *

Submit

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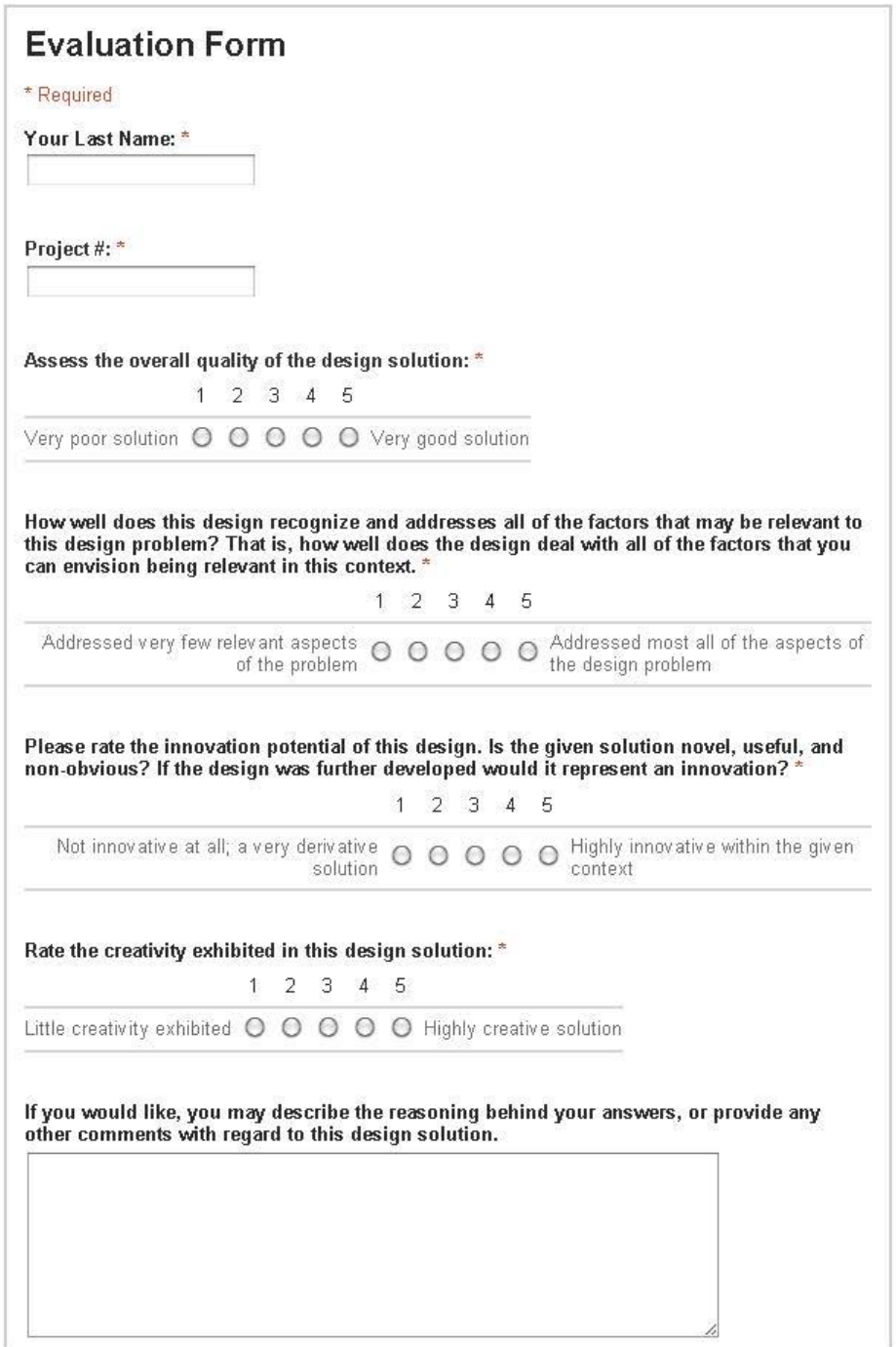
Figure H.1: Evaluator background survey.



Evaluation Form

* Required

Your Last Name: *

Project #: *

Assess the overall quality of the design solution: *

	1	2	3	4	5	
Very poor solution	○	○	○	○	○	Very good solution

How well does this design recognize and addresses all of the factors that may be relevant to this design problem? That is, how well does the design deal with all of the factors that you can envision being relevant in this context. *

	1	2	3	4	5	
Addressed very few relevant aspects of the problem	○	○	○	○	○	Addressed most all of the aspects of the design problem

Please rate the innovation potential of this design. Is the given solution novel, useful, and non-obvious? If the design was further developed would it represent an innovation? *

	1	2	3	4	5	
Not innovative at all; a very derivative solution	○	○	○	○	○	Highly innovative within the given context

Rate the creativity exhibited in this design solution: *

	1	2	3	4	5	
Little creativity exhibited	○	○	○	○	○	Highly creative solution

If you would like, you may describe the reasoning behind your answers, or provide any other comments with regard to this design solution.

Continued

Figure H.2: Evaluation form used by experts to evaluate student design projects.

Figure H.2 continued

Appendix I: Evaluator Results

Project #:	Evaluator ID:	Overall quality	Relevant factors	Innovation potential	Creativity	Total	Comments:
1	1	4	3	4	4	15	
1	2	5	5	5	5	20	
1	3	3	3	2	3	11	
1	4	5	5	5	4	19	
1	5	4	3	3	4	14	No cost analysis was completed for the new design
1	6	3	3	3	3	12	
1	7	4	4	4	4	16	
1	8	3	3	3	3	12	Is this a 1to1 or 1tomany communiction device? What about different groups having the same devices? How can I tell who communicated?
1	9	3	4	3	3	13	Could be developed more in depth. Solution is a possible fix for these problems, but unsure if it is truly considering the needs of the user.
1	10	4	4	5	5	18	What makes your design less expensive than the radio? Will this work with the existing dive watch, or will the user have to use this device in addition to his or her dive watch?
1	11	3	3	3	3	12	What is the communications range?
1	12	4	4	4	4	16	
1	13	4	2	3	4	13	watch face = 2D; world = 3D. how to convey direction of signal?
1	14	5	5	5	5	20	
1	15	4	4	4	4	16	Creative use of known technology - low cost solution.
1	16	5	4	5	4	18	
1	17	5	5	4	4	18	
1	18	5	5	4	3	17	Looks to be a very simple and helpful solution to underwater communication, at a reasonable cost ... but don't see it as very creative.
1	19	4	4	4	4	16	Sounds great and creative, but it's difficult to tell if the idea encompasses technology from the patent itself, or "magic buttons" that do what the designers want. None the less, they referenced the patent and the technology, which shows a more thorough thought process.
1	20	3	2	4	4	13	Issue with diver location in 3 dimensions on 2 dimensional watch face not addressed.
1	21	3	4	3	4	14	Not sure if this is an inexpensive solution
1	22	5	4	5	4	18	A novel solution to a common problem within the scuba/snorkel community. Directional lights displaying who is communicating to them presents a problem, as a watch face depicts two dimensions and in the scuba/snorkeling world, often persons are separated in 3 dimensions. The design team might consider how to depict if someone is above or below them - perhaps through the use of color.
1	23	5	5	5	5	20	Wow, great idea. Concerns: how will the devices handle interference from other ultrasonic noises? Is battery life a concern? Maybe it could be like an automatic watch, which recharges itself based on the wrist's movement.
1	24	5	5	5	4	19	I like the idea of using an existing invention in a different from factor. However this is just a design evolution. Like the GPS devices that moved from hand-held to watches. One the positive side, there is nothing wrong with copying an idea.
1	25	4	4	4	4	16	This seems innovative in that the signals are simple and familiar (lights and vibrations on phones/beepers/etc. are established attention-getters). Presumably, activating the signals would be easy when fully equipped in scuba gear (are hands covered? limited dexterity?).
1	26	4	3	3	3	13	
2	1	5	4	4	4	17	
2	2	3	3	2	3	11	
2	3	3	3	3	3	12	
2	4	5	5	4	4	18	
2	5	4	3	3	4	14	Not sure how this design will address the width of an obsese person and the potential heavy weight
2	6	2	1	1	1	5	
2	7	1	3	1	2	7	there is no prototype, no design to judge here. there are lots of ideas, lots of talk, and i can see how these principles are applied in their original contexts, but too much is left to me to assume how it will be applied to the context described.
2	8	4	3	3	3	13	
2	9	2	3	3	2	10	Not clear how the final piece is executed. Project seems to address relevant issues and care has been taking in considering manufacturing, but overall solution has not been presented and is thus difficult to evaluate effectively.

Continued

Table I.1: Evaluations of student design projects.

Table I.1 continued

2	10	3	3	3	3	12	It was difficult to visualize the design because of the disjointed images. Under carriage wheels on a backboard could increase strain on rescuers while they try to hold backboard in place to line up under carriage wheels.
2	11	3	3	3	3	12	Im not sure I understand it clearly. The narrative is too wordy and the images do not help clarify design intent
2	12	2	3	1	2	8	
2	13	3	2	2	3	10	
2	14	4	3	4	3	14	The text is a bit confusing here. I am not sure that I understand the proposed solution. Salient details are missing, but could easily be supplied through even crude drawings.
2	15	2	2	3	3	10	With no prototype to review it is difficult to understand how some of these design elements would function together or even as stand alone design features. The one that stands out in my mind is the "pivoting tracks". I'm picturing a 400 lb guy strapped to a board with wheels somehow being tilted so it can be slid onto the tracks and then pushed/pulled onto the stretcher? The victim and board are low to the ground so I'm picturing multiple EMT's pushing from their knees... while somehow keeping the stretcher from sliding...?
2	16	4	4	3	4	15	
2	17	4	3	4	3	14	
2	18	3	3	3	3	12	Drawbacks include complexity, multiple parts, and non-universality. Not overly creative.
2	19	2	3	2	2	9	It was impossible to actually see and understand what was designed. A picture of a shopping cart, dolly, and moment arm with fulcrum, don't show the actual design. I have no idea what the design actually is. Pictures are worth a thousand words, hence the two page constraint of their report.
2	20	4	4	3	3	14	
2	21	3	3	3	2	11	I found this design hard to understand from the illustrations. Ideas seem very basic -- wheels, fulcrum assist.
2	22	2	2	2	1	7	Where is the product? Many words were used to describe the product, but are ultimately ambiguous and meaningless without a simple prototype to associate with the words.
2	23	2	2	1	2	7	I understand the concept they are trying to communicate, but the image of the product is entirely in my own head and therefore might vary widely from this team's intent. I guess I just don't understand how it works or what makes it better than a regular backboard.
2	24	3	2	2	3	10	The lack of sketches or model makes it hard to visualize the operation of this design. I can envision that the backboard needs to thinner than the patient so the fulcrum is at the CG of the person. Did the designers address the lack of accessability to the wheel to lock or unlock them?
2	25	4	4	4	4	16	It seems that the overarching design principles are rooted in the science of simple machines rather than overly complicated devices. Using fulcrums/levers to get the patient onto the board and then to get the board onto the stretcher seem like elegant solutions.
2	26	2	5	4	3	14	I think they really thought through the problem, but require too much imagination on the part of the evaluator to figure out how their solutions actually works. Cannot tell if it's actually innovative. BETTER VISUALS NEEDED.
3	1	1	1	2	2	6	
3	2	3	2	3	3	11	
3	3	2	2	2	2	8	
3	4	3	3	2	3	11	I question how the top or roof would open during normal handling by a top loading truck?
3	5	3	3	3	3	12	I think the new lid will get in the way and have a tendency to break. In addition, it will be difficult to always walk to the back side to throw garbage into the dumpster
3	6	2	1	4	1	8	
3	7	3	3	3	3	12	
3	8	2	2	2	3	9	Seems counterintuitive alltogether. The original problem seems like a maintainance and not a design issue to me. Judging from the pictures of the new solution rain and snow can come in from the side, smell problem is mentioned, I can't follow the solution. Large cover seems harder to empty than before.
3	9	3	4	2	4	13	Good thought process, but not a terribly innovative solution. Unclear how this makes life easier for trash collectors and unconvinced that the smell will remain reduced.
3	10	4	3	4	4	15	Will this invite more animals to root in the dumpster? How does the redesigned shape make it easier for the truck drivers to prevent deforming the dumpster?
3	11	2	2	2	2	8	
3	12	4	4	2	4	14	
3	13	3	4	2	2	11	
3	14	3	3	4	3	13	
3	15	2	2	2	2	8	providing a lead-in angle for the lift fork is a good idea... even if you agree with the assertion that lack of air circulation and moisture are the root cause of the smell (which I don't), adding side openings isn't particularly innovative. Also, those side openings present a problem when emptying the dumpster as trash can fall through them (current dumpsters often have a side opening and include a sliding door). The handles located at the high point of the cover would seem to be difficult to reach... I don't understand how the open channel at the base of the cover would close it..?

Continued

Table I.1 continued

3	16	3	4	3	3	13	
3	17	2	2	2	1	7	I would be concerned with open dumpsters because I believe the current designs are closed to deter rodents. I'm also not sure how the shape has really changed to help the garbage collecting trucks easily lift the dumpsters. I think a lot more creativity could have been used to develop a more innovative solution.
3	18	1	1	1	1	4	Maybe I missed something, but I can't see this design improving the quality of dumsters for the depositors or the haulers very much, if at all ... the maintenance and complexity of use would seem to increase rather than go down ... and the cost of implentation for minimal, if any, gain would most likely be signficant ... and again the depositor would bear most of the increased cost.
3	19	2	3	3	3	11	Animals?!?! Racoons would LIVE in these! I also don't understand how the cover actually keeps out the elements, as it is wide open on the side. Rain will blow and drip in.
3	20	3	3	3	3	12	
3	21	2	3	1	2	8	Not much creativity exhibited
3	22	4	3	4	4	15	It's unclear as to how the lid swings open to allow the truck to collect the refuse when it is full - if there were large items in the dumpster, would it damage the roof? Again, questions that come up because a good prototype was built.
3	23	4	3	4	3	14	What about keeping out animals? Is it actually a feature that air can circulate around inside the dumpster? I don't see how the redesign makes it any easier for the garbagemen to get the forks lined up with the dumpster. It is cool that they redesigned a dumpster - it's not something I would have thought of, but they do have lots of problems currently.
3	24	1	2	1	1	5	It seems that the design group only observed one sector of the user population. Interviewing other users could have told them that having open dumpsters is a bad idea. Open dumpsters attract animals such as rats, raccoons, dogs, crows, flies and bees. The roof may interfere with the operation of the truck and obstruct the view the truck driver who needs to insert the forks.
3	25	3	3	2	3	11	The redesigned shape to help make the dumpsters easier to lift by the trucks seems like the same issues would still exist. Also, I imagine most residential dumpsters are closed for a reason...? I imagine critters being more attracted to an open dumpster. ?
3	26	4	5	2	3	14	
4	1	3	5	3	3	14	The "Attachment loop Design" is not explained very well. This is the first mention of the "movement assistance band" with no explanation of what this is or how it works. Is it the same as the "belt and clip closure" explained in the "Closure system Redesign" section?
4	2	4	4	3	3	14	
4	3	3	3	2	3	11	
4	4	4	5	5	4	18	The two pockets are very good, however the lift loops while good in concept would require study to optimally locate them to provide the most benefit to the assisting person and to minimze discomfort and / or injury to the patient. The call button concept of being with the patient anywhere is fine. Will the assisting person require then locating technology for patients who are mobile?
4	5	4	5	4	4	17	Solutions are practical with minimal cost impact
4	6	3	4	3	3	13	
4	7	3	3	3	3	12	the proposed design solution addressed 5 gown factors and 1 non-gown factor (the call button). the first 2 design modifications, the pockets for telemetry box and catheter were well thought out and considered functionality and needs in response to various users. The other gown feature designs, the attachment loop and closure system were far less successful. Creative thinking is evident in the suggestion that attachment loops to the gown may help medial staff to move a patient. however, the inherent structure of the garment and its material and fabrication are not suited to withstanding such forces. Where in the earlier 2 feature designs, testing/functional prototyping seemed to take place, t does not seem to have been carried out to the same level in this case. What if one student had worn the gown and laid as dead weight while another attempted to move him/her with the proposed handles? even if they didn't break, i'm sure the person wearing the gown would have felt some discomfort. The multifaceted purpose of the loopes make more sense in the context of points of attachment for other devices such as the call button. as for the closure re-design, the proposal of a hook and loop is baffling. It seems overly complicated. Perhaps it was better explained in a functional demonstration. it would have been better to know more as to why ties are used in the first place--even if there is no good answer, but to have some evidence about what the users--patients and medical staff express as benefits and/or weaknesses of the ties and use that as the basis of the re-design. Some clearer identification of the constraints, in addition to needs might help here. Even considering the constraints listed: frequent washing under high temps, would the clip system hold up? What about cost constraints? the 5th design, the call button integration has potential but the description is confusing without a larger image of the prototype. the description makes it sound that the call button is attached to a gown loop but then is activated by tearing that loop away from

Continued

Table I.1 continued

							the gown, which would create several issues. If instead the call button has a loop-like handle that is pulled for activation, that makes more logical sense but in that solution there are issues as well, such as how to re-set it or to make repeated calls.
4	8	4	4	4	5	17	Very creative. Practicability and affordability could be an issue
4	9	4	4	4	4	16	Efficient and effective solution; does not re-imagine much in a truly innovative way, but puts a spin on old ideas. A sensible and pragmatic update based on user-centered research.
4	10	5	5	4	4	18	The design problem was clearly stated, and the solutions clearly addressed the problem(s) described.
4	11	2	2	2	3	9	The actual problem is not clear to me. There are multiple little attachments added to the gown that could represent an improvement but it is not clear to me what and if they make sense in a single gown
4	12	4	4	4	5	17	I like how this design is rather simple solutions to obvious problems that apparently were never addressed in the previous design of the gowns. I like how it addressed many different problems with a single new device (the new gown has many different additions, but is still a 'single' gown that addresses many problems). The only one I did not like was the loops on the gown for movement. I see what they were trying to do, but I had trouble picturing this working effectively. Gowns are traditionally loose (for comfort and other reasons), and using loops attached to the gowns to move patients or help sturdy them does not seem like it will work. Again, maybe I am picturing this wrong.
4	13	3	2	3	2	10	
4	14	3	3	5	3	14	The problems pointed out with the existing design of hospital gowns and call buttons are indeed fairly serious problems, and the proposed solutions, while not going far enough in their development, seem to be a clear improvement to current designs. They also appear to be reasonably inexpensive changes. However, these designs seem tentative. The reader must struggle to envision how the proposals would actually work due to lack of illustration. Solutions as proposed are more draft than final.
4	15	3	3	2	2	10	- see-through pocket is simple, clean solution. - catheter bag holder... yes, bag is hidden but; location at inside/bottom of gown is tougher to access, the hanging weight wants to open the gown when banging against patient's leg... introduces increased likelihood of connection failures (bag and tube)..? - belt system...yes, tying the bottom tie is difficult however it seems that the belt only secures one side of the back opening... also the adjustment of these type of belts seems less intuitive and harder to manipulate for older people. Also, the belt would seem to present a tangling issue when cleaning the gown. - call button integrated into gown. Could be a good idea but the description / pic doesn't give enough detail to understand the concept. Not sure the new system is an improvement (pull cord vs. button) without more info.
4	16	4	4	3	3	14	
4	17	3	3	3	3	12	These solutions were a good start to the redesign of a hospital gown. They identified the issues at hand and found solutions that would likely work. I thought there could have been some more creativity and in-depth look from a patient's perspective. When you think of a patient in the hospital, you would imagine that they wouldn't want to be in the hospital in the first place. Comfort is the first thing that comes to my mind, and I don't get the feeling that adding call buttons, cather, tie belt, etc. would add comfort while wearing the gown.
4	18	3	3	3	2	11	Based on experience, additional weight, especially when unbalanced, tends to deform a loosely fitting garmet ... this change in shape can cause discomfort and awkwardness. Maintenance of the gown will most likely increase with the proposed additions, as durability decreases. Loading and unloading the gown may create an additional challenge. Don't find this solution a particulary creative.
4	19	4	5	4	5	18	Being as the driving force behind the design of the current gown is cost, it would have been nice to see a cost analysis of the current gown vs the proposed gown. I know this is difficult to do, but just comparing the amount of additional processes to produce the gown (i.e. sewing additional loops), even if no costs were assigned to these processes, would have shown thorough understanding of the constraints on the design.
4	20	4	5	2	3	14	
4	21	4	4	3	5	16	Many simple but very practical ideas were offered.
4	22	4	4	4	3	15	
4	23	4	4	2	3	13	I don't see the attachment loops staying attached. They'll rip off easily, and also, even though the straps may make it easier for the nurses to move the patient, I could see the strap cutting into the patient because it is narrow and unpadded.
4	24	4	3	5	4	16	I consider the first two ideas (the pockets) very innovative. These design solution seem so simple that I makes me wonder why have nobody implemented them yet. The last two ideas (attachment loop and call button), while innovative, I may see how the research was well done and makes me wonder: • Are there any hazards that can come up with long belts • Will the patient or nurse have the dexterity to deal with the clip closure at the end of the belt? Do the loops really make a difference? • The call button attached to the gown is a nice idea but I do not see how it would work if the patient leaves the bed. Wireless devices as strongly discourage from hospital rooms, so, how is it supposed to work?
4	25	3	3	2	3	11	I feel that the solutions stayed very much in the vein of the existing design -- modifications to existing features of the gown.

Continued

Table I.1 continued

4	26	3	4	3	1	11	The presentation of the prototypes was very poor. The overly small photos made it very hard to evaluate the implementation of their ideas. However, it seems like they had thought through their context and the needs of various users pretty well. I was a little iffy on the belt loop/patient lifting idea. I'm unconvinced the gown would be strong enough for that (especially repeatedly). The group also did not address how their proposed changes would affect the hygiene/washing issues around hospital gowns. I would have liked to see them tie that back in.
5	1	5	5	4	4	18	
5	2	5	4	5	5	19	
5	3	4	3	3	3	13	
5	4	4	4	4	4	16	I find the design creative in that it uses readily available sign posts. Two areas could have demonstated a higher level of creativity. First the mounting studs appear to be extended out of the box which could injure a rider while the box is in the stored position. My second comment would be why have the tool box opening on the bottom and not on the side opposite the mounting studs which would allow better access to tools, etc. when the bike is mounted in the stand.
5	5	4	4	4	4	16	Low cost solution that seems like it some merit
5	6	2	2	3	2	9	
5	7	4	4	5	4	17	aesthetics notwithstanding this approach demonstrates that the students looked well beyond the confines of the bike and other precedents to propose a thought provoking and clever solution. the multi-purpose aspect of the design to hold tools is a nice touch, but the access panel needs a lot more work. similarly: what if you ride a bike with a dropped top bar, or perhaps even a vintage woman's bike or cruiser? these considerations could be addressed in future prototypes but the initial conceptual thinking is strong.
5	8	3	3	4	4	14	Creative solution. Some questions still unclear: target audience? Weekend biker or enthusiast/pro? Usage? Around a race/tour with others? If everyone had one of those than poles would be in high demand. How easy is it to add to the pole? from the picture it looks cumbersome. how heavy is the device? Every gram counts.
5	9	5	5	5	5	20	Unexpected solution, surprisingly small, cheap, useful, and effective. Clear outside-the-box thinking with good potential for innovation.
5	10	5	5	5	5	20	This is definitely a simple design that addresses the identified problem.
5	11	3	3	3	4	13	The primary design goal seems to be lifting both wheels at the same time. That is not well established in the problem statement
5	12	5	4	5	5	19	Very creative. I really liked the idea of using something in the riders typical environment (sign posts) within the design. The only issue is what if the rider is riding on trails or other places where there are no street signs? The device renders itself useless. But very cool design solution none the less.
5	13	5	4	5	5	19	
5	14	3	4	4	3	14	Obvious limitations for non-urban use, but good potential for use in the city, such as by couriers.
5	15	3	3	5	5	16	surprised me when I saw the design.. nice idea, minimal parts, could also make out of high strength plastic. very good description of the problem and visuals of the competition (baseline). my only issue is not all bikes have a flat crossbar, all women's and some men's bikes have an angled crossbar which would have issues with this product... otherwise very clever.
5	16	5	4	5	5	19	I liked this design because if its simplicity and functionality. It sounds like at least one designer would also be an end user and had a very good understanding of user wants and needs.
5	17	5	4	5	5	19	I thought this idea was a great alternative to what's in the current market. I would love to see something more flexible to be used on any pole or post. I'd imagine if you're riding 50-100 miles, you could be on trails where there might not be available sign-posts.
5	18	5	5	5	5	20	If I was an avid bicycle person, I would buy the proposed kit as designed ... definitly innovative and creative. Protection from theft is the only issue that comes to mind.
5	19	2	2	2	3	9	Although creative, it didn't address the entire reason for wanting a bike stand to travel with you. If the students asked the user group these questions, they'd understand what tasks are looking to be performed on the move (i.e. adjusting derailleur, changing a flat, etc.). These tasks are all easily performed easier and faster by flipping the bike than by looking for a street sign to hang the bike on. Real bike stands are used for serious tasks that require tools you would never ride with because they are too heavy and bulky (BB tools, wheel tools, etc.). That was a long way of saying I don't see the point.
5	20	5	4	5	5	19	Good use of commonly available infrastructure to solve problem. Tool pocket is a nice feature.
5	21	4	5	4	3	16	
5	22	3	2	3	3	11	leveraging road signs is a novel use for lifting a bicycle in the air. However, it creates the necessity to require a particular type of road sign - which is plentiful on a college campus, but how common are they on bike trails, etc. My question to this team would be to ask them to make a more universal design that would allow them to attach to any vertical structure within a given size - including circular pipes and small trees - to be able to reach out to not only road cyclists, but also mountain bikers.

Continued

Table I.1 continued

5	23	5	5	3	4	17	I would use larger wingnuts to make it even easier to tighten or untightened. The final product would need to be less bulky. Maybe try to combine it with other bicycle products, such as a light, a pump, etc? Or add additional holders for those items? Could it be modified to allow it to attach to telephone poles when riding out in rural areas with fewer signs?
5	24	4	4	5	5	18	I find this design innovative. As a bike rider, I have not seen anything like this before. On the other hand, I c cannot think of an occasion where I had to put by bike on a stand in the middle of a bike ride. Whenever I had a flat tire or a broken chain, I had only to turn by bike upside down and the bike supports itself between the seat and the handle bars. I can see where there a few folks that would be interest in having such item. I also find it a solution for times where I wanted to park and chain by bike to a street sign and not have worry about the bike tipping over and scratching the paint (I know some cities prohibit chaining bike to street signs and parking meters).
5	25	5	4	5	5	19	I think this is an elegant solution. Is it going to be useful in every potential situation? No (break down where there are no road signs). But will it be useful in most situations? I imagine yes. This solution really solved the problem (how to repair/tweak bike when out and about?) instead of keeping within conventions of existing bike stands (i.e. redesign/modify an entire stand-alone bike stand to make it more portable).
5	26	5	5	4	5	19	I liked this one. Didn't make it overly complicated, actually solved a problem, created a multitasker.
6	1	3	1	4	2	10	
6	2	4	4	4	4	16	
6	3	3	2	2	3	10	
6	4	4	4	3	4	15	Specialized option potential would be nearly limitless. Could a storage holster add versatility?
6	5	3	3	3	3	12	Wooden end will break over time and doesn't appear durable. Userr will get frustarted with the product
6	6	3	2	3	2	10	
6	7	2	2	2	3	9	very derivative solution. context and constraints suggest other more salient opportunities for exploring mobility. i.e. how does a person in a wheel chair access an existing garden that is not in pots but out in an uneven landscape?
6	8	3	3	2	3	11	Customizable end seems gimmicky rather than innovative. Claw end can be an improvement over existing solutions.
6	9	3	3	3	2	11	I'm not really sure why this is better. It seems like just subtle variations on an existing tool.
6	10	4	4	4	4	16	
6	11	4	3	4	3	14	
6	12	3	2	2	3	10	Did not see much difference in capabilities and performance as current 'grabbers' that exist already
6	13	3	3	2	4	12	
6	14	4	4	4	4	16	
6	15	3	3	3	3	12	More attention could have been given to the customizable end to address universal attachments... driving a wood screw in and out of a piece of wood would only work for a limited period of time and is not exactly a user friendly process for an elderly person... for example, many broom heads and paint rollers use a universal thread so a standard broom handle can be used to sweep and paint (high or low places).
6	16	4	3	3	4	14	
6	17	3	4	3	3	13	
6	18	4	5	4	4	17	Creative idea and could be very helpful to many ... but it does require tailoring for each individual's circumstance ... plus it requires considerable overall refinement, both ends, before entering the market.
6	19	4	4	4	5	17	Makes you wonder why this doesn't exist yet. Simple and seems effective.
6	20	4	4	4	4	16	Issues of longevity of tool when using wood screw to affix different heads or rubber-band wear over time not addressed. Good use of both ends of device.
6	21	5	4	4	5	18	
6	22	2	2	3	4	11	This prototype allows for the design team (as well as Linda) to simulate how this could be used in the daily life of someone with limited mobility. As such, it affords the evaluator of the design to ask the following questions: A bendable wire requires the user to reshape the tool - which is great, so long as the user is up to reshaping the tool for every task they would like to operate. Would Linda do this? The use of the opposite end of the device is a good insight, but the execution is not feasible - using wood to accept a single screw will work, but screw holes grow old with time and use, creating the need to use larger and large screws to ensure a tight fit. Also, screws imply the need to drive a screw into the wood - which is a specific

Continued

Table I.1 continued

							combination of gross and fine motor skills that persons with arthritis have. Simply asking Linda if how would she modify one of her garden tools to fit on this device would reveal the need for some alternate means of attachment.
6	23	3	4	3	4	14	How hard will it be for a user with arthritis and/or limited mobility in one arm to change the head out on the end of the claw? The actuator could also be larger or more ergonomic, because as it is, it looks like it might be a little difficult or uncomfortable for arthritic users (their primary users) to grasp.
6	24	5	5	5	4	19	While this looks to be just an evolution of designs currently on the market, while reading this project I ask myself, if this is a simple solution why don't we see this in the market place. I think this is a good marketable idea: having multiple end factors. It seems that this group did their work well by observing the use or misuse of such devices by the end user.
6	25	4	4	3	3	14	The modular system is innovative -- different fixtures for different needs. But the idea of a grabber or extended reaching device is not novel.
6	26	3	2	1	2	8	
7	1	2	1	2	2	7	
7	2	3	2	3	3	11	
7	3	4	4	3	4	15	
7	4	4	3	5	4	16	In this design application the dolly will need to be capable of functioning in many different settings and terrains. I believe that the design team, while working to keep the cost of the dolly affordable overlooked a safety issue in that there is no mention of brakes, and that the center of gravity is pretty high to be stabile in uneven terrain.
7	5	3	2	3	4	12	Not sure how this design will address the width of an obeses person and potential heavy weight
7	6	1	1	1	1	4	
7	7	4	4	3	4	15	the proposed design seems to be well thought out in many aspects of its function-- namely the integration of all the pieces for the prototype. As we are not to evaluate the quality of the prototype, this may not be relevant. What is important is how all these features really work in the proposed situation. There is evidence that these thoughts/imaginings/projections into that context are taking place. Showing a person with the prototype is helpful but deceiving as she does not represent an obese person. even taking measures to increase her size (having her wear a heavy winter coat or wrapping her limbs with bubble wrap to increase their dimension) might have revealed other issues with the product. Additionally, the main users of this product would be the firefighter and there is no visual expression of how the firefighters would have to stand, sit or bend while working with and using the product.
7	8	2	2	3	4	11	Dignity and state the rescued heavy person is in are issues. Tying someone to a dolly is questionable. Obese person might not fit in this construction.
7	9	2	2	2	2	8	Did not address problems inherent with the backboard, did not consider variation among bariatric patients in terms of size, usage, personality, consciousness, or emotional response. Did not seem to identify nor solve significant problems in any new or meaningful way.
7	10	3	2	3	4	12	There seems to be a serious design flaw: the dolly requires the patient to be able to provide a certain amount of support for his or her own body via the legs. Many injuries (and drugs administered at the scene of an accident) may make this an unreasonable expectation.
7	11	3	1	2	2	8	This solution only seemed to consider the firefighter needs but the bariatric patient's needs were not clearly addressed. As a mechanical solution it may be intriguing but I would worry about how will the patient feel being carried around like a "heavy load"
7	12	5	4	5	5	19	Very good idea - I happen to know an EMT that complains about this issue all the time. I would be curious to see it in action, and see if and how it would be changed to allow for stair travel.
7	13	4	3	2	3	12	
7	14	2	2	2	2	8	I would like to know what type of medical problems may arise from rotating a patient from the supine position to the anatomic position. Could a bariatric patient, particularly one in distress, support themselves in the anatomic position? Assuming that a partial incline position is safe, would a wheel barrow design allow safer and easier movement of a patient, particularly over rough surfaces like gravel or grass? Even if this possible shortcomings have not been solved due to time constraints, I believe that the authors should at least acknowledge them in their texts.
7	15	2	3	3	3	11	Leverage is great but I'm picturing a 400 lb version of your model strapped into this BERD. What stabilizes the patient from falling forward, is there enough physical space to fit a 400 lb person (like you show in the picture)? your petite model appears to be wider than the board already... side handles (and wheels) help lift a patient but also get in the way when loading the patient onto the board.
7	16	3	2	3	4	12	Are existing backboards wide enough for these patients? While it is nice to use existing equipment, if it is not sufficient for the situation, it is not going to be a useful solution. I addition, does this only allow two fire fighters at most to move the patient? It seems like the handles being on the ground would make it difficult to begin lifting the patient. In general, an decent idea but needs some additional development.

Continued

Table I.1 continued

7	17	4	3	4	4	15	I like the idea of using a dolly, and this would reduce the number of firefighters that you would need to rescue an individual. The team really thought through the solution to ensure that the dolly was portable and compact for specific uses. I evaluated the team on a 3/5 on addressing problems because I would imagine that moving the dolly through different terrain would be fairly difficult. Although the solution states they did not address areas like stairs, it sounds fairly difficult to move someone on a dolly through an uneven path.
7	18	4	4	4	3	15	Good but not a universal solution. Average creativity.
7	19	4	4	4	5	17	The hideaway wheels were a creative space saver, but it would have been nice to see this device in the spot on the truck where the current stretcher goes. This would have addressed the constraint of storage space on the truck.
7	20	3	2	3	3	11	Issue of moving unconscious or otherwise injured human in a position where load of patient's weight was placed on legs was never addressed. Design features were well thought out, including hide-away wheels and flexibility for comfort of dolly operators. Basing the design around equipment most likely to be already deployed in field (backboards) was a good choice.
7	21	3	2	2	2	9	Only addresses 1 narrow issue -- handling heavy patients
7	22	3	3	3	5	14	I think this project exhibits a tremendous amount of innovation and creativity. From the project description, and photographs, it seems that this team might have created more problems in the process of trying to solve others. For instance, the thought of lifting a bariatric person to an upright position may create an unstable pivot point. In other words, if a bariatirc person was incapacitated (e.g. from smoke inhalation) would standing them up on their feet with tight straps all around them be able to support their disproportionate weight and not fall over - potentially causing more harm to the person or first responders. Understanding that this is a conceptual prototype and not fit for full scale testing, it seems that the mental simulation of envisioning a 500 lb person that is unconscience (and is nothing but dead weight) would result in different design decisions.
7	23	1	1	1	1	4	I disagree about "being low cost" being a priority. This is a potentially life-saving device - fire departments already spend tons on other equipment, and this is just a drop in the bucket. This thing seems just as big as other existing solutions. How can you maneuver this if a house is on fire or collapsing? How does a severely obese person fit on the backboard? It seems way too narrow for the first person picture. And what if you accidentally drop the person while transitioning them from lying down to upright? It doesn't appear to help assist the firefighters with actually getting the person onto the device itself, which is also critical.
7	24	3	3	4	5	15	I like the many features that were incorporated to the design (hide-away wheels, multi-position handles, leverage holds and auxiliary wheels). The design seems to work for a person of small to medium built as shown in the pictures. However, the invention needed to be tried with truly large people. I have a problem trying to envision this design for someone that weighs 400 lbs or more. Moving large load through a house full of obstacles and narrow hallways is difficult enough for the large person by themselves. This dolly design has the potential to hinder the movement even more in those narrow places. This may be a good solution for open spaces where a gurney is not available. I see the scope of design to be very narrow.
7	25	3	3	4	3	13	How is the patient put onto the device in the first place? Wouldn't he or she need to be lifted onto the backboard? Is orienting patients in a vertical position ever permissible? Reapplication of known technologies/devices for cost savings is definitely a form of innovation.
7	26	2	3	2	2	9	I felt like this team missed a couple opportunities. 1. They did not consider the dignity or emotional state of the person being moved with this equipment. 2. They did not show us people using their prototype, to illustrate how it actually makes moving someone easier (instead they just showed skinny girls strapped in). It is not apparently that they actually thought about the logistics of putting a very large person on this device. It is still very narrow.
8	1	5	3	2	1	11	
8	2	5	5	5	5	20	
8	3	3	3	2	3	11	
8	4	5	4	3	5	17	My concern with this design concept is how likely is the production cost of the system going to be affordable to those who would benefit from the device.
8	5	4	4	4	4	16	Well thougthout and should work. May get costly and not practical
8	6	4	4	5	5	18	
8	7	3	3	3	4	13	
8	8	5	4	5	4	18	Questions about affordability and practicability
8	9	3	3	3	3	12	Decent first step, but isn't a true solution yet.
8	10	5	5	5	5	20	
8	11	2	2	2	2	8	
8	12	5	5	5	5	20	Very good idea. Maybe have the scanner/indicator come in more options that a wristband for those who don't wish to wear one, like a necklace.

Continued

Table I.1 continued

8	13	2	1	3	3	9	
8	14	5	5	5	5	20	A simple but thoughtfully designed device. Having experienced a father suffering from late stage cancer, I can attest to the difficulty of regulating and dosing medication as needed, as well as the difficulty of refilling prescriptions, communicating with the Doctor's office, etc.
8	15	4	4	4	4	16	This project above all others I've seen so far merits additional study. Although there are many details to be resolved, the overall idea is very intriguing... I like the flexibility designed into the system, uses current technology to great advantage... I could see an App being developed for something like this.
8	16	5	4	4	4	17	
8	17	4	4	4	4	16	I like the idea of a dispensing mechanism for pills, but the technology integration may (I hate to say) be complicated for the user.
8	18	4	3	4	4	15	Definietly innovative but ... concerned about the dependability and cost of the product ... human or device errors could create major liability issues ... cost must be important as many elders live on a fixed income ... in addition, will many of the medicated require an operator to make sure the machine is set up correctly?
8	19	5	5	5	5	20	This should exist. OSU should be on the patent, now. The difficulty is in changing the system, as this product proposes, but the mp3 player is a product that changed the system.
8	20	3	3	3	3	12	
8	21	4	4	4	5	17	Very creative solution to a very real problem.
8	22	5	4	4	4	17	A few areas of this design that should've been further developed: 1) a large, senior friendly display 2) overall quality/reliability would be critical to avoiding incorrect doses and litigation This is an excellent example of how a good prototype can raise more questions, and therefore make you more aware of the context of the system that the product exists in - namely, a hopper that dispenses pills at a given time is a helpful solution to help ensure patients are taking all of their medication at the appropriate time. However, other development concerns arise - such as variation in pill size, number of medications that can be stored, and does the system know that the user actually took the drugs? What if they don't want to wear a watch? Is there a necklace version? or a phone app? All of these are items that would be fleshed out in the development process, but the point is that this concept and prototype allow the development team to see all of these issues clearly.
8	23	3	3	3	3	12	It's a good idea, but it seems to underestimate the challenge of how to handle different sizes of bottles and how to dispense pills of varying dimension and mass. How would it handle liquid medications? What about injections?
8	24	5	5	5	5	20	This is a solution that I can see in the market today after a few refinements. It was though very thoroughly.
8	25	3	3	3	3	12	I think aspects of this solution are innovative (real-time data sharing with pharmacies to aid with dosage, control, and refills). However, I feel that the solution is displacing effort/challenges. If a patient is mentally or physically impaired (and having trouble with their current medication system), how will they handle scanning/dealing with alarms/snooze button/refilling hoppers/etc.? I'm not sure this solutions is tackling the stated problems.
8	26	4	4	4	5	17	They left out the need to travel and take meds with you. People often carry meds that need to be take with food to restaurants or friends houses. Also, people travel. How does this device work when not at home?
9	1	3	3	3	4	13	
9	2	4	4	4	5	17	
9	3	3	3	3	3	12	
9	4	5	5	5	5	20	
9	5	4	3	3	3	13	Maybe difficult for dentist / hygienists to use on a regular basis. Not sure this idea will be used on a consistent basis.
9	6	3	3	3	3	12	
9	7	4	4	4	4	16	
9	8	5	4	4	4	17	
9	9	3	3	3	3	12	Seems like a minor solution to a minor problem. Seems bulky and unnecessary given the scale of the problem and solution.
9	10	4	4	5	5	18	Will the patient feel the air being blown across the mirror?
9	11	4	4	3	3	14	
9	12	5	5	5	5	20	I really like this idea! As the son and brother of a dentist I know that they would enjoy this ideas potential. I like how they paid attention to not messing with the feeling of the original tool - dentists are very particular about their equipment and what they are used to
9	13	2	3	2	2	9	
9	14	5	5	5	5	20	
9	15	5	5	5	5	20	Well thought out concept, prototype accurately portrays the concept, CAD model of quick disconnect is great. Every aspect of the design seems feasible.

Continued

Table I.1 continued

9	16	4	4	3	4	15	
9	17	3	4	3	4	14	
9	18	4	4	4	4	16	Appears to be a very helpful design solution ... potential areas that might become challenges include, 1) effectiveness of the air flow, 2) decreased freedom of movement of the dentist, 3) increased maintenance requirements, and 4) durability? But if these do not develop into significant drawbacks, then the design could be a winner.
9	19	4	4	3	4	15	It would have been nice if the group proved that spraying compressed air at glass actually cleans the surface as intended (from debris, moisture). Testing this with shop air and showing that it works would exhibit a more thorough design consideration. As it stands, it sounds like a great idea...if the concept itself works (not to be confused with "if the product works". I hope this makes sense).
9	20	3	2	4	4	13	
9	21	5	5	4	4	18	Well thought out and practical solutions
9	22	5	5	5	5	20	
9	23	4	4	4	4	16	The air might also cause debris to smear the mirror. Would pressure be low enough so as to not affect the patient or procedure?
9	24	5	5	5	5	20	The device seems to solve the problem as stated.
9	25	3	3	2	3	11	
9	26	3	3	3	2	11	This seems a little contrived.
10	1	4	2	5	4	15	
10	2	3	3	3	3	12	
10	3	2	2	2	2	8	
10	4	4	3	4	3	14	
10	5	4	3	3	3	13	I think the same issue will be present over time. Dirt, insect larvae and etc. will build-up in the mechanism.
10	6	3	2	1	1	7	
10	7	1	1	2	2	6	this is a mechanical solution. the benefit to the user might be that the tool doesn't break and using it might take less time, but what about the weight and cost of the tool?
							what about the entire cable box, and not just its locking mechanism?
10	8	3	3	2	2	10	It is a better key not a radically different solution
10	9	3	3	3	3	12	"Foul the tool on insertion" would be a great name for a 90s-era industrial/goth cover band. :-)
							...and "Bees in the Box" would open for them.
10	10	4	4	5	5	18	
10	11	3	4	3	3	13	The image is not sufficient to clearly understand design intent. From the narrative it seems like there was a good understanding of the problems with the current tool and that each problem was addressed in the new tool
10	12	2	3	2	2	9	
10	13	3	2	2	3	10	
10	14	3	3	3	3	12	I simply don't have enough explanation to evaluate how this device works. Even rudimentary drawings or more detailed photographs would allow me to evaluate more effectively. I might be able to infer how this works from the text, but I may be wrong or missing something essential.
10	15	4	5	4	4	17	high quality prototype gives me confidence that the idea has been more thoroughly vetted.. innovative solution that seems to eliminate many of the current issues while improving the ease of use aspect of the lock.
10	16	3	3	4	3	13	A CAD drawing with a section view would really help with the description...
10	17	4	4	3	3	14	
10	18	4	4	5	5	18	Looks like a good, innovative, and creative design ... my major concern would be the cost of box and implementation, and, thus, the cable user having to bear the brunt.
10	19	3	3	3	3	12	Again, I apologize if these values are lower than they should be, when the design itself is not communicated, it's impossible to tell if it is any good. Why aren't there images and flow diagrams showing me how this thing works!
10	20	2	2	3	2	9	
10	21	4	4	3	3	14	
10	22	4	5	4	4	17	
10	23	2	1	1	1	5	They designed a new lock? Why not just buy a different, better lock and position it differently?
10	24	4	4	3	3	14	This solution is very similar to how wafer-tumbler locks work.
10	25	2	2	2	3	9	"It would be much better to simply key the lock open..." They said it themselves...
							The solution seems highly engineered for the problem at hand. I think leveraging existing devices/mechanisms would have been a more creative solution (because it would be more executable).
10	26	3	4	3	3	13	Again, too hard to envision.
11	1	5	3	5	2	15	
11	2	4	4	5	5	18	

Continued

Table I.1 continued

11	3	3	2	3	3	11	
11	4	4	3	3	4	14	
11	5	3	3	3	3	12	Idea has been around. People may not accept redesign due to loss of privacy.
11	6	4	3	5	3	15	
11	7	3	3	4	4	14	
11	8	4	4	4	4	16	Like the creativity behind it. Not convinced about practicability (odors, wetness, dripping) while transporting
11	9	5	5	5	5	20	Clever, innovative, useful. Seems to address all major problems while maintaining integrity of existing solution.
11	10	3	4	4	3	14	
11	11	4	2	3	4	13	Not sure all of the user's needs were considered but this is a novel approach
11	12	2	1	1	2	6	I don't want a gym bag with two bulky fans on the side
11	13	3	3	4	4	14	
11	14	5	5	5	5	20	
11	15	4	5	5	5	19	The most innovative design of the group...I really like the thought given to active as well as passive drying features in the bag! Made a really good attempt to prototype this concept... good visuals in the description. Of course, nothing will ever replace a washing machine... ;-)
11	16	5	4	5	5	19	
11	17	2	3	2	2	9	
11	18	2	2	2	4	10	Creativity is the strong suit, but there are several potentially significant drawbacks to include: 1) added weight primarily from the fans, 2) odor produced by the fans, 3) durability of the fans, 4) complexity of the design (definitely not KISS), and 5) practical, convenient useability for a young person.
11	19	4	4	4	4	16	The fans don't point at the equipment when the bag is rolled out, but this could be reworked. Also, the bag being "flexible" may be a constraint that they didn't identify. Those fans are rigid, and therefore may break if the bag is tossed around, shoved in a locker, etc. The unraveling, mesh gymbag is a great idea though.
11	20	2	2	3	3	10	
11	21	3	4	3	5	15	
11	22	3	5	3	4	15	While the solution to the problem statements are addressed, the prototype reveals the affordances of existing sports bags - namely that they conceal what is in them - I'm curious if users would buy into this design, simply due to it's transparency. If this prototype were brought back to a locker room, how would athletes respond?
11	23	1	1	1	5	8	Who lays their sweaty clothing out to dry after working out or playing a sport? You're not supposed to re-use it, you're supposed to wash it! If you make the bake more porous to let moisture evaporate, it also means your gear will get soaked when it's rained on. I don't want my sports bag to be even heavier because it has fans and batteries in it. I don't want to give up that much space inside. I don't want to plug in my bag to recharge it! Seriously, a bag with two huge fans on it?! It's a, uhh, creative design, but also pretty terrible.
11	24	3	3	4	5	15	I believe that the principals of the invention are good. However, mesh bags exist right now and they are not popular. There has to be a reason for that.
11	25	3	2	3	2	10	
11	26	5	5	5	5	20	I love that they show their solution/prototype in action. Also, good storytelling to help get the point across.
12	1	3	4	5	4	16	The solution idea is clear, but the details are not. More detailed explanation is needed.
12	2	3	4	4	4	15	
12	3	3	3	3	3	12	
12	4	3	3	2	3	11	In my opinion the design applies a solution to a small segment of the potential population of users. The track width of wheel chairs varies significantly from model to model which would greatly complicate the feasibility of implementation of the proposed concept. While facing rearward may be safer in a frontal crash there may be disadvantages in other types of crashes and evacuation situations.
12	5	4	3	4	4	15	Well thought out and should supply a solution to an everyday problem. Will need bus manufacturer to agree and accept
12	6	2	1	3	1	7	
12	7	2	2	2	2	8	there are so many factors of the system that are discussed in the background but are not addressed. do all the seats need to be flipped up? what about eliminating the hairpin turns? The proposed design only accounts for a small part of the problem space. the introduction of ergonomic issues is not positioned as a big concern in the initial background, and should be, if being used to defend the design proposal.
12	8	2	2	2	2	8	Laudable to address a problem that handicapped people face when using public transportation. Certain things are still unclear to me though: how big of a space is needed, would the 5 seats currently there be removed (highly impractical for older people that rely on sitting down while using the bus (there are a lot more old people using buses than people in wheelchairs. Would it be cheaper for the bus company to

Continued

Table I.1 continued

							pay for a taxi everytime than implementing this solution? Would a person in a wheelchair want to face everyone in the bus while traveling. Would he/she want to travel backwards?
12	9	1	3	1	2	7	Lots of unclear elements in this project. Not sure where the restraints come from, not sure how people get out, not sure if wheelchair wheels are the same width or if there is variation that might affect this from working. Solution could be effective, but presentation of solution is glossed over and unclear, making it very difficult to truly evaluate.
12	10	4	3	4	4	15	The design is simple, but would require retrofitting entire fleets of buses, likely requiring construction to the floor. This may make it unaffordable. Consideration of the likely direction of movement of the wheelchair rider and addition of the headrest are useful.
12	11	4	2	4	4	14	This is a complex problem that requires further study but has potential for further development.
12	12	3	2	3	3	11	
12	13	1	1	2	2	6	
12	14	3	4	5	4	16	This is a very interesting approach to chair restraint, although the proposed "friction lock" solution at this stage of development would probably not be sufficient to resist the forces encountered during an accident. Still, a good start to a well-explained problem.
12	15	1	1	3	3	8	Just a quick review of wheelchair dimensions on various websites indicates that there are a number of wheel center-lines (width) which would make this concept very difficult to execute. Also, this design concept does not appear that it could fulfill SAE J2249 - "Wheel chair tie-down and restraint systems for use in motor vehicles".
12	16	2	1	2	1	6	Doesn't seem like the students spent much time with this redesign. This doesn't seem like a very secure method of holding wheel chairs, probably isn't cost effective, and would it be difficult to get out of the grooves depending on the slope leading into them.
12	17	4	4	5	4	17	
12	18	4	4	4	3	15	Not a bad idea. Major concerns from my point-of-view are 1) ensuring the wheels are propoerly secured in the mechanism and 2) that the mechanism holds during a sudden slow-down or stop. Don't see notable creativity.
12	19	3	3	3	3	12	I wonder if they asked the user group if they would prefer riding facing forward or backward. In addition, there is no fail-safe in the design (a redundant strap through the wheels, for example), and they didn't look into how easy or impossible it is to implement.
12	20	2	2	3	2	9	Issue of retro-fitting or designing necessary actuators and sensors into buses was somewhat glossed over. Problem of preventing wheelchair from rotating about axle of secured wheels during accident not addressed.
12	21	3	2	3	2	10	
12	22	4	4	4	4	16	I am concerned about the alignment process with this design - what happens if you are a half inch off center, what if you are four inches off? Does applying force perpendicular to the wheel rotation direction at the moment arm an inch above the ground put undue pressure on the axle of the wheel and therefore damage the chair? In the case of an accident, how much force is required to secure the chair and passenger? does that amount of force damage the chair?
12	23	4	3	5	5	17	How much variation is there in wheelchair designs? Are they confident this design could accommodate them all? On the whole, a very intriguing solution though.
12	24	3	2	3	3	11	The design has not been though through. It has not taken into account different wheel chair design and dimensions. It does not include any possible preventive mechanism for damage the chair wheels'. How about consideration for a dirty bus floor? I've been in buses where there is a lot of garbage and debris on the follow that can get lodge in the clamp thus rendering the mechanism inoperable. Why is a head rest needed? No one else in the bus has a head rest. Why did the sharp turns mentioned at the beginning of the problem statement? I would think that more maneuvering will be necessary to get the chair in the floor grooves.
12	25	3	2	3	3	11	How would such a design accommodate many different types of wheelchair wheels? Does the new restraint system fold/tuck away to allow for non-handicap seats to be used in its place when no wheelchair passengers are on board? A problem seems to be that the wheelchair user has a hard time navigating to position his or herself to be strapped in. Hows does this help that?
12	26	1	3	2	2	8	I feel like they missed a lot.
13	1	4	1	3	2	10	
13	2	4	4	4	4	16	
13	3	2	3	2	3	10	
13	4	5	5	5	5	20	
13	5	4	4	4	4	16	Logical solution to an everyday problem
13	6	2	2	2	1	7	
13	7	3	3	3	3	12	unclear of how all parts are used in concert. prototype alone is well crafted but without context it cannot be evaluated properly.

Continued

Table I.1 continued

13	8	3	3	3	3	12	Don't understand why it has to be disposable other than assuming to make more money. Not explained. Are ther any dangers of beeing a fixated device in a persons body that is under anasthesia?
13	9	3	3	3	3	12	Started okay, but how is this better? Must be hard to cram this in someone's mouth. If it's not meant to do that, it's not clear.
13	10	4	4	4	5	17	Connecting the mirror to the mouth gag is clever.
13	11	4	4	3	4	15	
13	12	4	4	5	5	18	Very neat solution. I wonder how surgeons would accept it. They are trained from the get-go to hold that mirror all the time and even use it as a tool (a blunt 'push things aside' type tool). Still, great idea
13	13	4	3	4	4	15	
13	14	4	3	4	4	15	
13	15	4	4	4	4	16	Innovative use of fundamental mechanical "concepts" to provide a hands free solution... I like the preliminary cost calculation.
13	16	4	4	4	4	16	
13	17	3	3	2	2	10	
13	18	4	3	4	3	14	I can see that, if it works as explained, the mirror could allow doctors to utilize a hand in other things than holding a mirror ... but I must ask if a doctor needs that hand free, and, if the answer is yes, does the solution provide for the control and precision necessary for the operations being performed ... as it would appear that some precision and control will be sacrificed. It would also seem that the mirror attached to the mouth gag would add clutter to the already small access to the area being operated on ... does this increase in cumberson clutter add interference to an already restricted access.
13	19	3	4	3	4	14	It was a struggle to understand how this works, but part of that was just being unfamiliar with the process and current tools. I like the imagery, but annotations (arrows, etc.) would have been nice to understand how it moves, and how it clips to the other device. The cost analysis was completely made up. Comical.
13	20	3	3	3	3	12	
13	21	4	4	5	4	17	
13	22	4	4	4	4	16	The prototype allows the evaluator to ask the question of if I would want that in my own throat - and with the square corners, my answer is no, but if the corners were rounded the design would be much improved.
13	23	4	3	3	2	12	
13	24	5	5	5	5	20	The device seems to solve the problem as stated.
13	25	3	3	3	3	12	Clamping to the mouth gag makes sense, although how would the additional weight of the mirror affect the gag?
13	26	4	4	4	4	16	
14	1	3	1	3	2	9	
14	2	4	5	4	4	17	
14	3	3	3	3	3	12	
14	4	5	5	4	4	18	
14	5	3	3	3	3	12	Minimal market for device and doesn't seem worth investing time and money into it
14	6	3	2	3	1	9	
14	7	3	2	4	3	12	
14	8	4	5	5	4	18	Didn't know the problem existed in the first place. Seems like a very plausible solution.
14	9	1	1	1	1	4	This project jumps into the middle of the story without laying appropriate groundwork. Not sure what the actual problem is that is being addressed. For those reasons, this cannot be effectively evaluated. It looks like there is a story here, but it is very specific and I have not been told what the specifics are.
14	10	5	5	5	5	20	
14	11	2	2	2	2	8	Im not sure I understand what the problem is so it is difficult to know how does the new design address the route setting process
14	12	4	4	3	4	15	
14	13	4	4	4	3	15	
14	14	5	5	5	5	20	
14	15	3	4	4	4	15	modern assembly is always driving toward tool-less processes so this is great... you should also point out the safety requirements and how they are addressed... also, how is the device meant to be disengaged..?
14	16	5	4	5	5	19	
14	17	3	3	4	3	13	
14	18	5	5	5	3	18	If I utilized rock climbing facilities and wanted to change my route while climbing, the design solution provided would be an excellent methodology ... having said that it is a good solution, I do not see more than average creativity in the solution.
14	19	3	3	3	3	12	Again, I cannot actually tell how this thing works. I read it several times, and looked closely at the images, but I don't know how the thumb button expands the device in the wall. I also don't see how it comes out of the wall, which is not addressed.
14	20	3	2	2	3	10	

Continued

Table I.1 continued

14	21	3	4	3	3	13	The problem,s with the present design were not well explained; making it difficult to knowledgeably assess the solutions
14	22	5	5	5	5	20	
14	23	4	4	3	4	15	
14	24	4	4	4	4	16	This could be a time saving device that could be attractive to climbers.
14	25	4	4	3	4	15	
14	26	1	1	1	1	4	How about some context? I have no idea what problem they are trying to solve or if the solution is even plausible.
15	1	5	4	5	2	16	
15	2	4	4	3	3	14	
15	3	2	2	2	2	8	
15	4	4	4	5	4	17	Potential sales and options for these backpacks would be extensive. Additonal creativity could use the concept of a space for each item and each item in it's space as an inventory assist and flags for associated low flags.
15	5	4	4	4	4	16	Solution is practical with minimal cost impact.
15	6	1	1	2	1	5	
15	7	3	4	4	4	15	overall quality is fair. the ideas sound great but there is no visual explanation or investigation as to how these ideas might be implemented. No prototype exists and without physical experimentation and testing, there really isn't a concept.
15	8	4	3	3	3	13	
15	9	3	3	3	3	12	Hard to evaluate without seeing any semblance of the proposed solution.
15	10	4	4	4	4	16	
15	11	3	3	3	2	11	Its hard to see what the design is, not illustration, image or prototype? if there was it is not clear from this material
15	12	3	4	2	2	11	
15	13	2	2	2	3	9	
15	14	2	2	2	2	8	Very underdeveloped. It would be helpful to have included the following: Weight, dimensions, and a more complete list of contents. I would think that the arrangement and accessibility of the "redundant" medical supplies in the ambulance offers at least some improvement over the need to root around for supplies in the first responders kit. I am not convinced that keeping supplies only in the kit would be an improvement. As in other projects, drawings would be helpful, as would more detailed photographs documenting the existing solutions.
15	15	2	3	2	1	8	It is hard to critique a design without a prototype to look at. Adding back-straps and magnets to a case does not seem particularly innovative and w/out a prototype, it is hard to understand how this concept would provide any improvement from the current case/process.
15	16	4	4	4	3	15	
15	17	4	4	3	3	14	It would have been nice to see a visualization of their concept. I think this idea could go a lot further in thought with how the first responders are using the kits.
15	18	3	2	2	2	9	Design is fine but don't see it as very innovative or creative ... at first glance, I can not imagine this change helping the first responders very much.
15	19	1	1	1	1	4	Ummmm, am I missing something...like the product! Hugely confused, and the description wasn't helping. All I got out of that was shoulder straps.
15	20	2	2	2	3	9	Magnetic mounting was not clear. If magnetic coupling is strong enough to mount box as workstation, wouldn't it be difficult to remove in an emergency situation?
15	21	4	5	4	5	18	Very comprehensive and well thought out approach.
15	22	3	2	2	3	10	Where is the product? Written words are descriptive of the product and the problem being addressed, however without a physical prototype, it is very difficult to establish and respond to the design teams' intent and solution to the problem. It is hard to see how the product would be used, and therefore assess whether or not it would be useful in this context without seeing the product.
15	23	3	3	2	3	11	Is there a prototype??
15	24	4	3	4	3	14	I like the idea to add shoulder straps to the hard case boxes, this is the latest trend in air travel soft-shell cases. Customizing of the interior of the vehicles is less of a novel idea (may be for this particular situation). With that said, does anyone know if customization is happening now? It could a profitable business if it does not exist already. I would like to have seen or read examples of the customization they group was thinking about.
15	25	3	3	3	3	12	
15	26	3	3	3	3	12	

Appendix J: Student CCMT Matrices

Stakeholders: 1 Regular Road Bicyclists

Refresh List

Highlight Interaction Depth: 1

Highlight Interaction Threshold: 3

ID	NAME	STAKEHOLDER	WEIGHT	DELTA	p1	p2	p3	p4	p5	p6	p7	t1	m1	m2	m3	u1	u2	u3	u4	u5	c1	c2
	Physical Constraints																					
p1	Small Profile	1	4	0		4	2	4	3	3	2	4	2	2	4	3	1			2	1	
p2	Length	1	3	2	4		1	4	4	3	3	3	2	1	3	3	2	2		1		
p3	Sturdy-attachment to post	1	4	0	2	1		3								4		3	1	4	2	3
p4	Lightweight	1	3	2	4	4	3		3	2					2		2			4		
p5	No interference with rider	1	2	1	3	4		3		4	3	4	4	4	2	3	1	1	1	2	1	1
p6	Fixture to bike (while riding)	1	3	3	3	3		2	4		2	4	4	4	2		3	2	2		2	3
p7	Fixture to bike (while fixing)	1	4	4	2	3			3	2		4	4	4	2	2	3	4	4		2	3
	Technological Constraints																					
t1	No interference with crucial parts	1	2	0	4	3			4	4	4		3	3		2	1	3	2	1	2	2
	Market Constraints																					
m1	Supports all size bike frames	1	4	0	2	2			4	4	4	3		4			4	3	1	1	1	1
m2	Supports all shape bike frames	1	3	0	2	1			4	4	4	3	4				4	3	1	1	1	1
m3	Holds all sizes multi-tools	1	1	2	4	3		2	2	2	2								4	1	2	1
	Usage Constraints																					
u1	Fits in standard road signs	1	4	0	3	3	4		3		2	2						4	3	4	3	3
u2	Frame attachment time	1	2	4	1	2		2	1	3	3	1	4	4				1	3	1	3	4
u3	Stays standing- hands free	1	3	1		2	3		1	2	4	3	3	3		4	1		2	2	2	1
u4	Access to storage while attached	1	1	2			1		1	2	4	2	1	1	4	3	3	2		2		1
u5	Sign post attachment time	1	1	4	2	1	4	4	2			1	1	1	1	4	1	2	2		3	4
	Cultural Constraints																					
c1	Familiar design	1	1	4	1		2		1	2	2	2	1	1	2	3	3	2		3		4
c2	Simple to understand	1	3	1			3		1	3	3	2	1	1	1	3	4	1	1	4	4	

Figure J.1: Student CCMT 1.

Stakeholders:

1 Firefighters
2 Obese Victim
3 Development Team

List

Highlight Interaction Depth: 1

Highlight Interaction Threshold: 3

ID	NAME	STAKEHOLDER	WEIGHT	DELTA	p1	p2	p3	p4	p5	p6	t1	t2	t3	m1	m2	m3	u1	u2	u3	u4	u5	u6	u7	u8	u9	u10	u11	c1	c2	c3
	Physical Constraints																													
p1	Fits in truck and/or on person	1	3	1		1	3	3	1	2	3	0	2	2	1	2	2	0	3	1	2	1	0	0	1	2	2	1	1	2
p2	Fits through home doorway	1,2	5	1	1		2	2	1	1	1	0	1	0	0	0	0	3	0	0	0	1	0	1	1	2	1	0	1	0
p3	Capable of withstanding 600lbs	2	4	3	3	2		3	3	4	3	1	3	3	2	3	4	1	2	3	0	1	0	0	3	3	4	1	0	3
p4	Holds an uneven weight dist.	1,2	4	0	3	2	3		0	2	1	0	3	2	1	2	4	2	3	3	1	1	0	1	3	3	3	2	0	0
p5	Durable against debris, bumps and drops	1	3	1	1	1	3	0		4	1	2	2	3	1	1	1	0	1	3	3	0	1	0	0	0	0	2	0	0
p6	Lightweight	1	2	1	2	1	4	2	4		3	0	2	3	1	2	3	2	1	3	0	1	0	0	2	3	3	4	3	0
	Technological Constraints																													
t1	Compatible with backboard	1	5	3	3	1	3	1	1	3		0	1	3	1	4	2	2	2	3	0	1	0	0	0	3	4	2	4	4
t2	Fire resistant	1,2	1	0	0	0	1	0	2	0	0		0	3	2	1	0	0	0	1	1	0	1	0	0	0	0	4	0	2
t3	Utilizes mechanical advantage	1	4	2	2	1	3	3	2	2	1	0		2	2	3	4	3	3	1	2	2	1	1	2	1	1	2	0	1
	Market Constraints																													
m1	Price Point	1	2	2	2	0	3	2	3	3	3	3	2		2	3	2	1	1	1	0	0	1	0	2	1	2	4	4	1
m2	Time to Market	1,2,3	4	3	1	0	2	1	1	1	1	2	2	2		0	1	0	2	0	1	1	0	2	1	3	4	4	2	2
m3	Unique from competition	1,3	3	2	2	0	3	2	1	2	4	1	3	3	0		3	1	2	3	2	1	1	2	1	4	0	3	3	1
	Usage Constraints																													
u1	Can be operated by 1 person	1,2	5	2	2	0	4	4	1	3	2	0	4	2	1	3		0	3	4	1	2	0	1	4	3	3	0	1	2
u2	Allows additional people to assist	1,2	3	2	0	3	1	2	0	2	2	0	3	1	0	1	0		2	2	1	1	0	0	1	3	3	0	1	2
u3	Quick to deploy	1,2	4	1	3	0	2	3	1	1	2	0	3	1	2	2	3	2		0	4	1	0	0	2	3	3	2	2	1
u4	Allows for restraint of victim	1,2	3	2	1	0	3	3	3	3	3	1	1	1	0	3	4	2	0		0	0	1	0	2	3	3	0	2	3
u5	Can be used without vision	1	4	4	2	0	0	1	3	0	0	1	2	0	1	2	1	1	4	0		1	0	3	1	0	0	2	0	3
u6	Can be operated by people of various heights	1	3	1	1	1	1	0	1	1	1	0	2	0	1	1	2	1	1	0	1		0	1	2	3	1	0	0	2
u7	Washable	1	3	1	0	0	0	0	1	0	0	1	1	1	0	1	0	0	0	1	0	0		0	0	0	0	3	0	4
u8	Quick cutaway in case of emergency	1	4	1	0	1	0	1	0	0	0	0	1	0	2	2	1	0	0	0	3	1	0		2	2	2	2	0	3
u9	Failsafe; prevents dropping victim	1,2	2	1	1	1	3	3	0	2	0	0	2	2	1	1	4	1	2	2	1	2	0	2		3	2	0	1	0
u10	Transports victim in standing position	2	4	2	2	2	3	3	0	3	3	0	1	1	3	4	3	3	3	3	0	3	0	2	3		4	3	3	3
u11	Can transport victim sitting or lying down	2	1	3	2	1	4	3	0	3	4	0	1	2	4	0	3	3	3	3	0	1	0	2	2	4		3	4	4
	Cultural Constraints																													
c1	Multi function / multi purpose	1	3	2	1	0	1	2	2	4	2	4	2	4	4	3	0	0	2	0	2	0	3	2	0	3	3		3	3
c2	Interfaces with common equipment	1	2	3	1	1	0	0	0	3	4	0	0	4	2	3	1	1	2	2	0	0	0	0	1	3	4	3		4
c3	Compatible with existing methods/techniques	1	2	4	2	0	3	0	0	0	4	2	1	1	2	1	2	2	1	3	3	2	4	3	0	3	4	3	4	

Figure J.2: Student CCMT 2.

Stakeholders:
1 Patients
2 Nurses
3 Mfg. & Assembly
4 Our Company

sh List

Highlight Interaction Depth: 1

Highlight Interaction Threshold: 3

ID	NAME	STAKEHOLDER	WEIGHT	DELTA	p1	p2	p3	t1	t2	t3	m1	m2	m3	u1	u2	u3	c1	c2	c3		
	Physical Constraints																				
p1	Stability	1,2	4	2		3	1			1		2		3	4					14	
p2	Base Size	1,2	2	1	3			1						2	3					9	31
p3	Rigidity & strength	2,3	3	1	1										4				3	8	
	Technological Constraints																				
t1	Battery Life	3,4	2	4		1			1			1	2	3	1					9	
t2	Power outlet interface	3	4	0				1								2	1			4	23
t3	Works with existing bags	2,3	4	3	1								1	2		4	2			10	
	Market Constraints																				
m1	IV Pump connector adapter	3	3	2								2	3			4	2	4		15	
m2	Price point	4	2	1	2			1			2		1		2	3	2		1	14	44
m3	Time to market	4	1	2				2		1	3	1			1	3	3	1		15	
	Usage Constraints																				
u1	Mobility	1,2	4	1	3	2		3		2					3	4		3	2	22	
u2	Weight & size	1,2	2	3	4	3	4	1				2	1	3		1	1		1	21	67
u3	Ease of setting up/taking down	2	3	2					2	4	4	3	3	4	1			3		24	
	Cultural Constraints																				
c1	Similar use as previous IV poles	1,2	1	1					1	2	2	2	3		1					11	
c2	Connect pumps via holes in pole	2	2	2							4		1	3		3			2	13	33
c3	Customizable movement (handle)	1	3	2			3					1		2	1			2		9	

Figure J.3: Student CCMT 3.

Stakeholders:

1 Patient
2 Nurse
3 Cleaning
4 Hospital

Highlight Interaction Depth: 1

Highlight Interaction Threshold: 3

ID	NAME	STAKEHOLDER	WEIGHT	DELTA	p1	p2	p3	p4	t1	t2	t3	t4	m1	m2	u1	u2	u3	u4	u5	c1
	Physical Constraints																			
p1	Access Location	1,2	3	1				2						1	4	1	2	1	4	
p2	Location of Call button	1,2	4	1					2			1	1	4	2	3		4	3	
p3	Washable	3	3	0							4		2	2						
p4	Body Closure	1,2	4	3	2								3	2	3	2	4	3	4	
	Technological Constraints																			
t1	Sensor Size	1,2	2	2		2				4	4	3	4	4		3		2		
t2	Battery Life	1,2,4	4	3					4		4		4	4						
t3	RFID	1,2,4	2	3			4		4	4		4	4	4						
t4	Adaquate Security	2,4	3	2		1			3		4		4	4						
	Market Constraints																			
m1	Price	4	4	2		1	2	3	4	4	4	4		3	1	1	1	1	1	
m2	Interfacing with Current Equipment	1,2,3,4	4	4	1	4	2	2	4	4	4	4	3		1	2		1		
	Usage Constraints																			
u1	Nurse Access	2,4	4	0	4	2		3					1	1			3	3	4	
u2	Weight/Size of Medical Equipment	1	2	1	1	3		2	3				1	2			1	2		
u3	Ease of Closure	1,2	3	1	2			4					1		3	1		3	4	
u4	Ease of Use	1,2	3	1	1	4		3	2				1	1	3	2	3		4	
u5	Ease of Access	1,2	3	1	4	3		4					1		4		4	4		
	Cultural Constraints																			
c1	Insecurity with catheter bag	1	1	0																

Figure J.4: Student CCMT 4.

Stakeholders:

1 Medical Staff
2 Patients
3 Hospital
4 Manunfactoring

List

Highlight Interaction Depth: 1

Highlight Interaction Threshold: 3

ID	NAME	STAKEHOLDER	WEIGHT	DELTA	p1	p2	p3	p4	p5	t1	t2	m1	m2	m3	m4	u1	u2	u3	u4	c1
	Physical Constraints																			
p1	Room Size	3	2	0		3		3												
p2	Wheel size & base	1,2	4	1	3		4	2	2					4			3	1	3	
p3	Structural Strength of stand	2,4	3	1		4		2	3			3		4	1		4		4	
p4	Compact	1,4	1	4	3	2	2		2			2		4		1	4	2	4	1
p5	Portable/light	1,2	3	1		2	3	2				2	1	3	1		3		3	1
	Technological Constraints																			
t1	Tube size compatibility	1,4	4	0								1	4	2		4	1			
t2	Magnetic Limitations	3	1	4								2	1	2			2		2	
	Market Constraints																			
m1	Cost	3,4	2	2			3	2	2	1	2		2	4	3	1	3	2	3	1
m2	Brand/ Generation Compatibility	3,4	3	3					1	4	1	2		1	4	2				1
m3	Safety	1,2,3	4	0	4	4	4	4	3	2	2	4	1		1	2	4	1	4	
m4	Time to Market	3,4	3	1			1		1			3	4	1		1	1		2	1
	Usage Constraints																			
u1	Easy to connect and disconnect tubes	1,2	4	1				1		4		1	2	2	1		1			
u2	ensure patient cannot harm self	1,2	4	0		3	4	4	3	1	2	3		4	1	1			4	
u3	Easy to Clean	1	2	2		1		2				2		1					1	
u4	Supports are strong enough to support patient weight and balance	2	4	1		3	4	4	3		2	3		4	2		4	1		1
	Cultural Constraints																			
c1	Homey feel	3	1	4				1	1			1	1		1				1	

Figure J.5: Student CCMT 5.

Stakeholders:
1 Handicapped People
2 Rehab Centers
3 Manufacturer

Refresh List

Highlight Interaction Depth: 1

Highlight Interaction Threshold: 3

ID	NAME	STAKEHOLDER	WEIGHT	DELTA	p1	p2	p3	p4	t1	t2	t3	m1	m2	m3	u1	u2	u3	u4	u5	u6	u7	c1	c2	c3
	Physical Constraints																							
p1	Physical Size/Footprint	1,3	4	1		3		1							3	3				2	1			
p2	Length of device	1,3	3	1	3		1	1							1	2				1		1		
p3	Material choice	1,3	2	2		1		4				1		4	3	2				3	1	1		
p4	Rigidity & strength	1,3	3	1	1	1	4					1		2	3	2				1	3	1		
	Technological Constraints																							
t1	Test																							
t2	Test																							
t3	Test																							
	Market Constraints																							
m1	Time to market	2	2	1			1	1						3	1	1				1	1	2		
m2	Price point	2	3	1			4	2				3			2	2				2	3	2		
m3	test																							
	Usage Constraints																							
u1	Weight/size of device	1	4	1	3	1	3	3				1	2			3	1	2	2	3	2	1		
u2	Size of end (area to push/pull)	1	3	3	3	2	2	2				1	2		3		3			2	2	1		
u3	Ease to place device down and easily pick up	1	3	1											1	3				2	1	1		
u4	Ease to make customizable ends	1	3	2											2			4	1	1		1		
u5	Ease to change customizable ends	1	3	2											2		4		1	1		1		
u6	Feel	1	3	1	2	1	3	1				1	2		3	2	2	1	1		4	2		
u7	Control Interface (lever for clamp)	1	4	4	1		1	3				1	3		2	2	1	1	1	4		2		
	Cultural Constraints																							
c1	Aesthetics	1	3	2		1	1	1				2	2		1	1	1	1	1	2	2			
c2	Test																							
c3	Test																							

Figure J.6: Student CCMT 6.

Stakeholders:
1 Police Officer
2 Police Horse
3 Mfg& Assembly

Refresh List

Highlight Interaction Depth: 1

Highlight Interaction Threshold: 3

ID	NAME	STAKEHOLDER	WEIGHT	DELTA	p1	p2	p3	p4	p5	t1	t2	t3	m1	m2	m3	u1	u2	u3	u4	u5	c1
	Physical Constraints																				
p1	Weight	1,2	4			4	1			1	3	1				4		1			
p2	Strap Material	1,2,3	2		4			4								4			1		3
p3	Length/Size Adjustment	1	4		1							1				2	4		3		3
p4	Weatherproof	1,2	4			4					3	3				2				4	2
p5	Light Mounts Location	1	2								2	3				3		4	1	1	3
	Technological Constraints																				
t1	LED size	3	1		1						4	1						4			2
t2	Battery/Power Supply	3,1	3		3			3	2	4		3				4		4	2		1
t3	Wiring	3	2		1		1	3	3	1	3					1				4	
	Market Constraints																				
m1	safety and visibility regulations	1,2,3	4		1	3	1	4	4	4	3	4				1	2	4	4	2	
m2	Test																				
m3	test																				
	Usage Constraints																				
u1	Feel/Bulkiness	1,2	3		4	4	2	2	3		4	1					2		3	2	4
u2	Proper Sizing	1,2	4				4									2			3		3
u3	Illumination Range	1	4		1				4	4	4										
u4	Ease of Removal & Donning	1	2			1	3		1		2					3	3				1
u5	Control Interface	1	2					4	1			4				2					2
	Cultural Constraints																				
c1	Aesthetics	1	3			3	3	2	3	2	1					4	3		1	2	

Figure J.7: Student CCMT 7.

Stakeholders:

1 Patients
2 Caregivers
3 Pharmacists
4 Doctors

Highlight Interaction Depth: 1
Highlight Interaction Threshold: 3

ID	NAME	STAKEHOLDER	WEIGHT	DELTA	p1	p2	p3	t1	t2	t3	m0	m1	m2	m3	u1	u2	u3	u4	c1	c2	c3
	Physical Constraints																				
p1	Has to hold medication	1,2,3	4	0		3	2	4		2	1	2			2		3	4		2	
p2	Has to be portable	1,2,3	3	2	3		3		3	4			2	1	1		3	2		2	
p3	Has to be safe and secure	1,2,3,4	4	2	2	3		3	4	2			1		3		2		3	3	
	Technological Constraints																				
t1	Must be compatible with pharma	3	2	3	4		3		2		4		2		1				2	2	3
t2	Internet/data connection for track	1,2,4	3	3		3	4	2		3	2		2	1	1		3	1	2	2	2
t3	Portability: power source and data	1,2	2	2	2	4	2		3		2		2	1	1		2	1			
	Market Constraints																				
m0	Can't take up a lot of professional	2,3,4	3	1	1			4	2	2			1		2			2		1	
m1	Can't take up a lot of patients' tim	1	1	3	2								1	1	4	3	3	3			1
m2	Affordable for people on Medicar	1, 4	3	2		2	1	2	2	2	1	1		1	1		2	2		1	1
m3	Can't be scary or condescending	1	2	3		1			1	1		1	1		3	3	2	2		1	
	Usage Constraints																				
u1	Can't be very complicated	1,2	3	1	2	1	3	1	1	1	2	4	1	3		2	3	4			
u2	Unwilling to cooperate	1, 2	1	3								3		3	2		1	1			1
u3	Impaired mobility and senses	1	3	1	3	3	2		3	2		3	2	2	3	1		2		1	
u4	Must account for multiple schedu	1,2,3,4	4	0	4	2			1	1	2	3	2	2	4	1	2			1	
	Cultural Constraints																				
c1	Government approval/licensing	1,3, 4	3	2			3	2	2											3	2
c2	Privacy/HIPAA	1, 4	4	1	2	2	3	2	2		1		1	1			1	1	3		
c3	Accommodate different language	1	2	4				3	2			1	1			1			2		

Figure J.8: Student CCMT 8.

Stakeholders: 1 User; 2 Garbage Truck Driver; 3 Manufacturer — Refresh List

Highlight Interaction Depth: 1

Highlight Interaction Threshold: 3

ID	NAME	STAKEHOLDER	WEIGHT	DELTA	p1	p2	p3	p4	t1	t2	t3	t4	t5	m1	m2	m3	u1	u2	u3	u4	u5	c1	c2	c3
	Physical Constraints																							
p1	Size	1,2,3	2	4		4	3	4	1	3			2	3		4	2	4		1	2	4	2	
p2	Weight	2,3	2	4	4		3	3	4	3			2	2		3		2			2	3		
p3	Shape	1,2,3	2	4	3	3		4		1	4	2	1	2		4	4	4		4	4	4	4	2
p4	Height	1	4	4	4	3	4			1			1	1		2	3	2		2	2	2	2	
	Technological Constraints																							
t1	Materials	3	3	2	1	4				3	1	3	3	3		1					1			
t2	Manufacturing Method	3	3	1	3	3	1	1	3			2	3	4										
t3	keeping trash dry	1		3			4		1			3		1			2	3	4	4	3	2	2	3
t4	keeping sun off of trash	1	2	3			2		3	2	3			2			2	3	3	3	3	3	4	3
t5	Repair	3	3	3	2	2	1	1	3	3				2										
	Market Constraints																							
m1	Cost	3	4	2	3	2	2	1	3	4	1	2	2			2								
m2	Location	2,3	4	0													2				2			
m3	Volume	1,2,3	3	4	4	3	4	2	1					2			2	4		2	1	4	2	
	Usage Constraints																							
u1	Throwing away small garbage	1	4	2	2		4	3			2	2			2	2		2		4	4	3		
u2	Throwing away large garbage	1	2	3	4	2	4	2			3	3				4	2		2	2	2	4	1	1
u3	Ease of Getting Trash into Dumpster	1	4	3							4	3						2						
u4	Contact with Dumpster	1	2	3	1		4	2			4	3				2	4	2				2		
u5	Ease of Emptying	2	4	1	2	2	4	2	1		3	3			2	1	4	2				2		1
	Cultural Constraints																							
c1	Size of trash that it can accept	1,2,3	2	3	4	3	4	2			2	3				4	3	4		2	2		1	
c2	Hide Trash from View	1,3	1	3	2		4	2			2	4				2		1				1		
c3	Smell/Odor	1,2,3	1	2			2				3	3						1		1				

Figure J.9: Student CCMT 9.

Stakeholders: Cops, Manufacturer, Motorola — Refresh List

Highlight Interaction Depth: 1

Highlight Interaction Threshold: 3

ID	NAME	STAKEHOLDER	WEIGHT	DELTA	p1	p2	p3	p4	p5	t1	t2	t3	t4	t5	m1	m2	u1	u2	u3	u4	u5	u6	u7	u8
	Physical Constraints																							
p1	Size	1,2	3	1		4	0	2	0	3	2	0	2	0	0	0	0	3	0	0	0	0	0	3
p2	Weight	1,2	3	1	4		0	1	0	3	0	0	2	0	0	0	0	4	0	0	0	0	0	0
p3	Color	1	2	1	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
p4	Durability	1	2	1	2	1	0		2	2	0	0	1	0	2	0	0	0	0	0	0	0	0	0
p5	force to push the button	1	3	3	0	0	0	2		0	0	2	0	2	0	0	2	0	4	4	0	4	4	0
	Technological Constraints																							
t1	Battery Life	1,2	3	2	3	3	0	2	0		0	0	0	0	4	0	0	0	3	3	2	0	0	3
t2	Ability to change between zones a	1	3	1	2	0	0	0	0	0		2	0	0	0	0	4	0	0	0	0	4	0	0
t3	Manufacturing	2	3	2	0	0	0	0	2	0	2		3	0	4	4	0	0	0	0	0	0	0	0
t4	Antena on the radio	1,2	4	3	2	2	0	1	0	0	0	3		0	2	0	0	3	0	0	0	0	0	0
t5	Setting pre-set	1,2	3	3	0	0	0	0	2	0	0	0	0		0	0	4	4	0	0	0	4	0	0
	Market Constraints																							
m1	Price	2,3	2	3	0	0	0	2	0	4	0	4	2	0		3	0	3	1	1	0	0	0	0
m2	Producability (high volume)	2,3	2	2	0	0	0	0	0	0	0	4	0	0	3		0	0	0	0	0	0	0	0
	Usage Constraints																							
u1	One hand accessability	1	3	1	0	0	0	0	2	0	4	0	0	4	0	0		4	4	4	4	4	4	0
u2	Portability	1	4	1	3	4	0	0	0	0	0	0	3	4	3	0	4		0	0	0	0	0	1
u3	Short talk	1	4	4	0	0	0	0	4	3	0	0	0	0	1	0	4	0		4	0	0	0	0
u4	Long Talk	1	4	4	0	0	0	0	4	3	0	0	0	0	1	0	4	0	4		0	0	0	0
u5	Volume	1	2	2	0	0	0	0	0	2	0	0	0	0	0	0	4	0	0	0		0	0	3
u6	pre-sets	1	3	3	0	0	0	0	4	0	4	0	0	4	0	0	4	0	0	0	0		0	0
u7	Panic Button	1	4	3	0	0	0	0	4	0	0	0	0	0	0	0	4	0	0	0	0	0		0
u8	Speaker	1,2	3	3	3	0	0	0	0	3	0	0	0	0	0	0	0	1	0	0	3	0	0	
	Cultural Constraints																							

Figure J.10: Student CCMT 10.

Stakeholders:

1 Landscapers
2 Average Users
3 Manufacturing Company

Highlight Interaction Depth: 1

Highlight Interaction Threshold: 3

ID	NAME	STAKEHOLDER	WEIGHT	DELTA	p1	p2	p3	p4	t1	t2	t3	m1	m2	m3	u1	u2	u3	u4	c1	c2	c3
	Physical Constraints																				
p1	Automatic Closure	1,2	4				2	2	2		1	3	3	3		1	4	4			
p2	Single opening for filling	1,2	4				4		1			3				1		1		3	3
p3	Single Vent	1,2	4		2	4		1			3	4	4		4	3		3	1		
p4	Material Choice	3	3		2		1			3		2		3		2		4			
	Technological Constraints																				
t1	How to open nozzle	1,2	4		2	1					1	4	3	4		4	4	3	4		
t2	Handle choice	1,2	2					3				3	3	3			2				
t3	Flow rate	1,2	2		1		3		1						4						
	Market Constraints																				
m1	Ease of Manufacturing	3	1		3	3	4	2	4	3			4	2			2				
m2	Number of parts	3	2		3		4		3	3		4		2		1	3		2		
m3	Price Point	1,2,3	3		3			3	4	3		2	2								
	Usage Constraints																				
u1	Smooth pour	1,2	3				4				4										
u2	Easy to open	1,2	3		1	1	3	2	4				1				4		4		
u3	Child Proof	1,2,3	4		4				4	2		2	3			4			3		
u4	No Leak	1,2	4		4	1	3	4	3												
	Cultural Constraints																				
c1	Intuitive Opening Design	1,2	3				1		4				2			4	3				
c2	Nozzle must fit to tank opening	1,2	4			3														4	
c3	Opening must fit to refil from gas :	1,2	4			3													4		

Figure J.11: Student CCMT 11.

Stakeholders:

1 Operators
2 Engineers
3 Maintenance

Highlight Interaction Depth: 1

Highlight Interaction Threshold: 3

ID	NAME	STAKEHOLDER	WEIGHT	DELTA	p1	p2	p3	p4	t1	t2	m1	m2	m3	m4	m5	u1	u2	u3	u4	u5	c1	c2	c3
	Physical Constraints																						
p1	Physical Space	1,3	4	1		3	4	3	2	1	2	3	2	2	2	3	4	3	3	1	2	4	3
p2	Pallet size	1	2	0	3		2	1	1	0	1	1	1	1	1	4	2	2	2	3	2	3	2
p3	Distance to conveyer	1	3	2	4	2		3	1	1	2	4	2	2	2	3	3	2	2	2	1	3	2
p4	Ability to turn	1	3	3	3	1	3		1	1	1	2	1	2	1	3	3	3	4	2	1	3	3
	Technological Constraints																						
t1	Automated	1,2	3	3	2	1	1	1		2	3	3	2	3	3	1	3	3	3	2	1	2	2
t2	Scanner accuracy	1	2	1	1	0	1	1	2		2	1	0	1	1	1	2	2	1	2	1	2	1
	Market Constraints																						
m1	Price point	2	3	3	2	1	2	1	3	2		2	3	2	3	2	3	2	2	2	2	3	2
m2	Integrate with current conveyor	1,2,3	4	4	3	1	4	2	3	1	2		3	3	3	3	3	3	3	2	2	3	2
m3	Time to market	2	2	3	2	1	2	1	2	0	3	3		2	2	1	3	2	2	2	1	3	1
m4	Production speed	1,2	3	3	2	1	2	2	3	1	2	3	2		2	2	4	4	3	2	0	3	3
m5	Start up time	2	3	3	2	1	2	1	3	1	3	3	2	2		1	2	2	1	1	0	3	2
	Usage Constraints																						
u1	Different heights of users	1	3	4	3	4	3	3	1	1	2	3	1	2	1		2	3	2	3	1	2	4
u2	Simplicity	1,2,3	4	3	4	2	3	3	3	2	3	3	3	4	2	2		4	3	3	1	3	2
u3	Intuitive to use	1,2,3	4	3	3	2	2	3	3	2	2	3	2	4	2	3	4		4	3	1	3	3
u4	Mobility of part	1	3	3	3	2	2	4	3	1	2	3	2	3	1	2	3	4		4	0	3	3
u5	Weight of transmission cases	1	3	0	1	3	2	2	2	2	2	2	2	2	1	3	3	3	4		0	2	3
	Cultural Constraints																						
c1	Aesthetics	1	1	3	2	2	1	1	1	1	2	2	1	0	0	1	1	1	0	0		1	1
c2	Similar to current process	1,2	2	3	4	3	3	3	2	2	3	3	3	3	3	2	3	3	3	2	1		2
c3	Safety	1,3	4	3	3	2	2	3	2	1	2	2	1	3	2	4	2	3	3	3	1	2	

Figure J.12: Student CCMT 12.

Stakeholders:
1 Owner
2 Dog
3 Public
4 Manufacturer

fresh List

Highlight Interaction Depth: 1

ghlight Interaction Threshold: 3

ID	NAME		WEIGHT	DELTA	p1	p2	p3	t1	t2	t3	t4	m1	m2	m3	m4	u1	u2	u3	u4	c1	c2	c3
	Physical Constraints																					
p1	Low weight	1,2	4	0		1	3	3			4		2		1	1	1	2	2	4	1	2
p2	non-abrasive	1,2	3	0	1		4			2					2	2	2		4	4	1	
p3	Material choice	1,2,3	3	3	3	4		4		2	3	3		2	1	1		3	1	3	2	3
	Technological Constraints																					
t1	leash strength	1,2,3	4	1	3		4				3	1			2	1				1		2
t2	retractor speed	1,2	2	4							2		1		1		3			4		1
t3	Adhesion Strength	1,2	2	2		2	2					1			1		4	3	2		2	3
t4	Retractor Size	1,2	4	0	4		3	3	2			2	2		2		3	2	2	3	3	3
	Market Constraints																					
m1	Price Point	1	4	4			3	1		1	2		1	1	1	3	2	2	2	1	2	2
m2	Size Variety	1,2	2	2	2				1		2	1			2	4					2	
m3	Time to market	4	1	4			2					1										
m4	Style Variety	1,3	1	3	1	2	1	2	1	1	2	1	2			2			1		4	4
	Usage Constraints																					
u1	Adjustability	1,2	3	1	1	2	1	1				3	4		2				3	4	2	1
u2	reatachability	1	4	0	1	2			3	4	3	2						3	2	2	1	3
u3	Sturdy handle	1,3	3	1	2		3			3	2	2					3		3	1	3	4
u4	Ergonomic Handle	1	2	2	2	4	1			2	2	2			1	3	2	3		1	3	2
	Cultural Constraints																					
c1	Doesn't hurt the dog	1,2,3	4	0	4	4	3	1	4		3	1				4	2	1	1		1	2
c2	Aesthetics	1,3	1	3	1	1	2			2	3	2	2		4	2	1	3	3	1		3
c3	Appearance of Durability	3	2	1	2		3	2	1	3	3	2			4	1	3	4	2	2	3	

Figure J.13: Student CCMT 13.

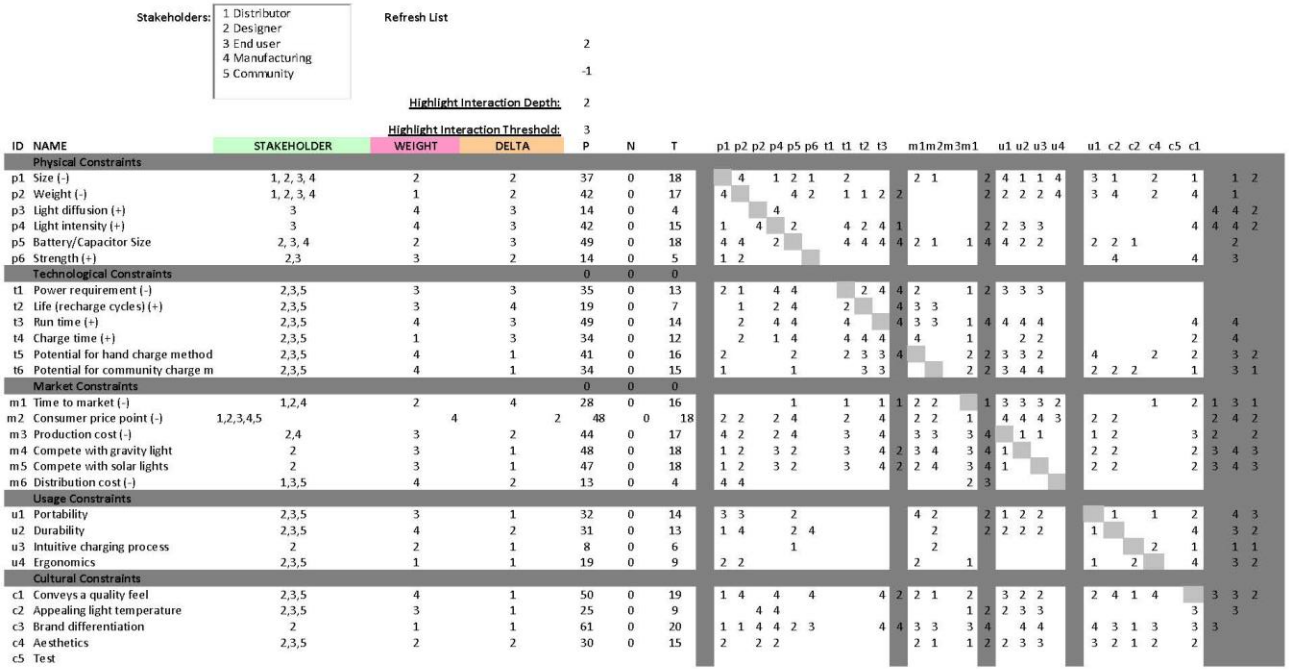


Figure J.14: Student CCMT 14.

Stakeholders:
1 Police Officers
2 Commercial Use
3 StakeholderC

Interaction Depth: 1

Interaction Threshold: 3

ID	NAME			DELTA	p1	p2	p3	p4	p5	p6	t1	t2	t3	t4	m1	m2	m3	u1	u2	u3	u4	c1	c2	c3
	Physical Constraints																							
p1	Adaptable to all Maglites	1	4	0		1	1	1	0	1	3	4	2	1	2			4	3	0	2			
p2	Not excessively long	1	3	2	1		3	4	1	2	1	3	0	1	1			3	0	0	0			
p3	Battery power	1,2	3	0	1	3		4	2	0	1	0	0	3	3			1	0	4	0			
p4	Battery layout	1,2	3	0	1	4	4		0	1	4	3	2	1	2			1	0	3	0			
p5	Weight	1	2	3	0	1	2	0		1	0	1	0	0	1			3	2	0	0			
p6	Attachability to other objects	1	2	2	1	2	0	1	1		3	1	0	0	1			0	1	0	0			
	Technological Constraints																							
t1	Easy removal of lights	1,2	4	0	3	1	1	4	0	3		4	4	0	1			0	2	0	3			
t2	Rigid structure on end of maglite	1,2	4	0	4	3	0	3	1	1	4		3	1	2			3	4	1	1			
t3	Automatic activation	1,2	3	1	2	0	0	2	0	0	4	3		3	3			0	2	0	2			
t4	Light function (strobe, etc.)	1,2	2	2	1	1	3	1	0	0	0	1	3		2			2	1	1	1			
	Market Constraints																							
m1	Affordable	1,2	2	3	2	1	3	2	1	1	1	2	3	2				1	4	3	4			
m2	Test																							
m3	Test																							
	Usage Constraints																							
u1	Useable on end as light wand	1,2	2	1	4	3	1	1	3	0	0	3	0	2	1				2	3	2			
u2	Durable	1,2	2	0	3	0	0	0	2	1	2	4	2	1	4			2		1	4			
u3	Bright		3	0	0	0	4	3	0	0	0	1	0	1	3			3	1		1			
u4	Waterproof	1,2	2	0	2	0	0	0	0	0	3	1	2	1	4			2	4	1				
	Cultural Constraints																							
c1	Test																							
c2	Test																							
c3	Test																							

Figure J.15: Student CCMT 15.

Stakeholders:
1 Scuba Divers/Snorkelers
2 Manufacturers
3 Retail/ Rental Companies

Highlight Interaction Depth: 1

Highlight Interaction Threshold: 3

ID	NAME	STAKEHOLDER	WEIGHT	DELTA	p1	p2	p3	p4	p5	p6	p7	t1	t2	t3	t4	m1	m2	m3	u1	u2	u3	u4	u5	c1	c2	c3
	Physical Constraints																									
p1	Physical Size/Footprint	1	4	2		1			1	4	1															
p2	Water Tight	1,2	4	0	1		1	3			2															
p3	Robust	1	4	1		1		4	1	3	2															
p4	Material	1,2	2	3		3	4		2	4	1															
p5	Brightness	1	3	2	1		1	2																		
p6	Weight	1	2	2	4		3	4																		
p7	Vibration	1,2,3	3	2	1	2	2	1																		
	Technological Constraints																									
t1	Radiofrequency	1,2	4	4									4													
t2	Battery Life	1,3	4	4								4		2												
t3	Light Underwater	1,3	3	3									2													
t4	Water Tight Buttons	1	4	0																						
	Market Constraints																									
m1	Time to Market	2,3	2	2														3								
m2	Price Point	1,3	4	2														4								
m3	Competition w/other communicat	3	3	2												3	4									
	Usage Constraints																									
u1	Underwater	1,3	4	0																4	2	3	1			
u2	User Interface	1	4	3															4			1	1			
u3	Communication Distance	1,3	3	4															2		4					
u4	Reliability	1,2,3	4	2															3	1	4					
u5	Feel/Comfort	1	2	4															1	1						
	Cultural Constraints																									
c1	Aesthetics	1,3	2	4																					2	2
c2	Percieved Need	1	3	4																				2		2
c3	Color Commuication	1	1	1																				2	2	

Figure J.16: Student CCMT 16.

Appendix K: Clustering Analysis for CCMT Reuse

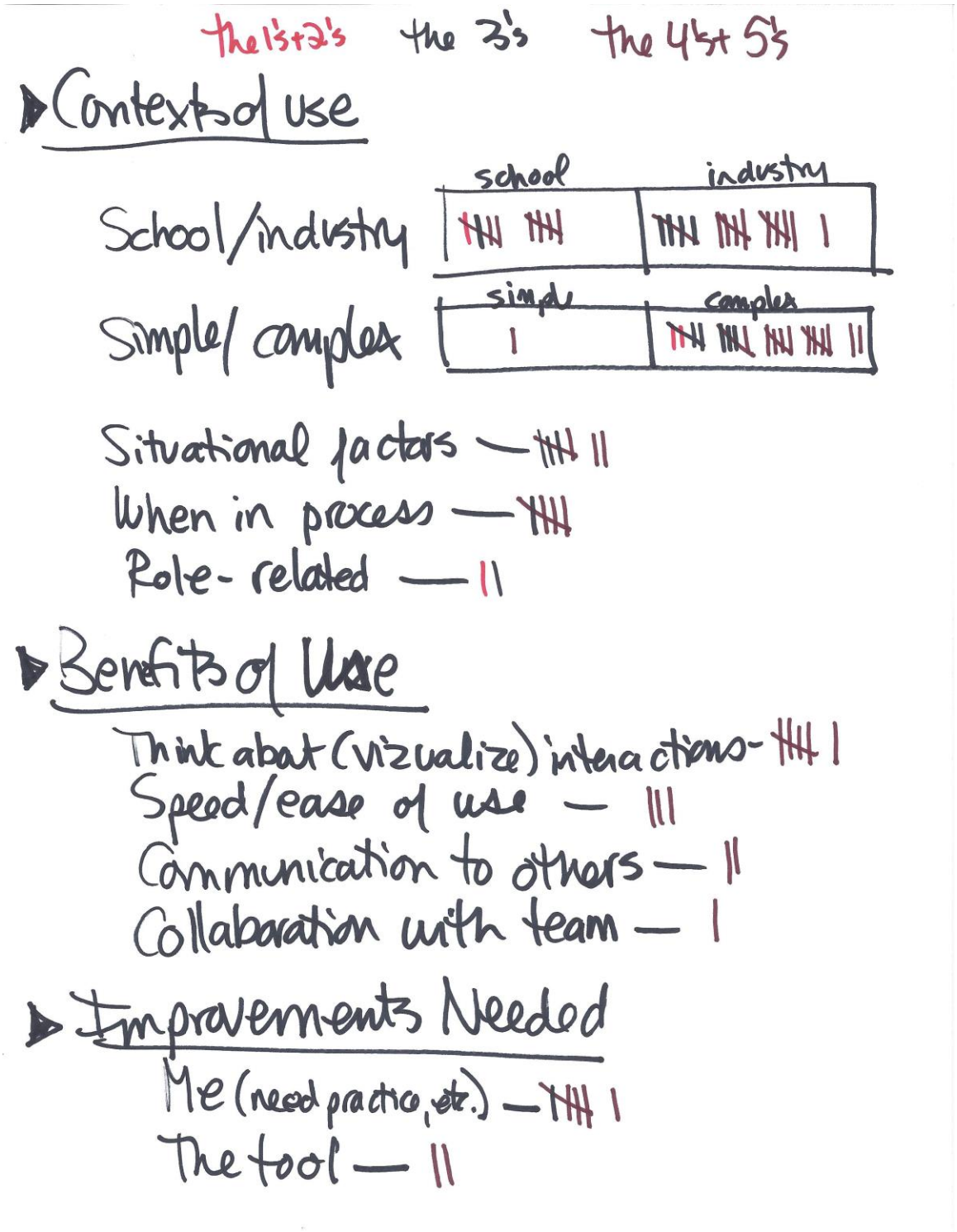


Figure K.1: Original clustering analysis conducted on student responses about CCMT reuse.

Appendix L: Like/Dislike Graduate Matrices

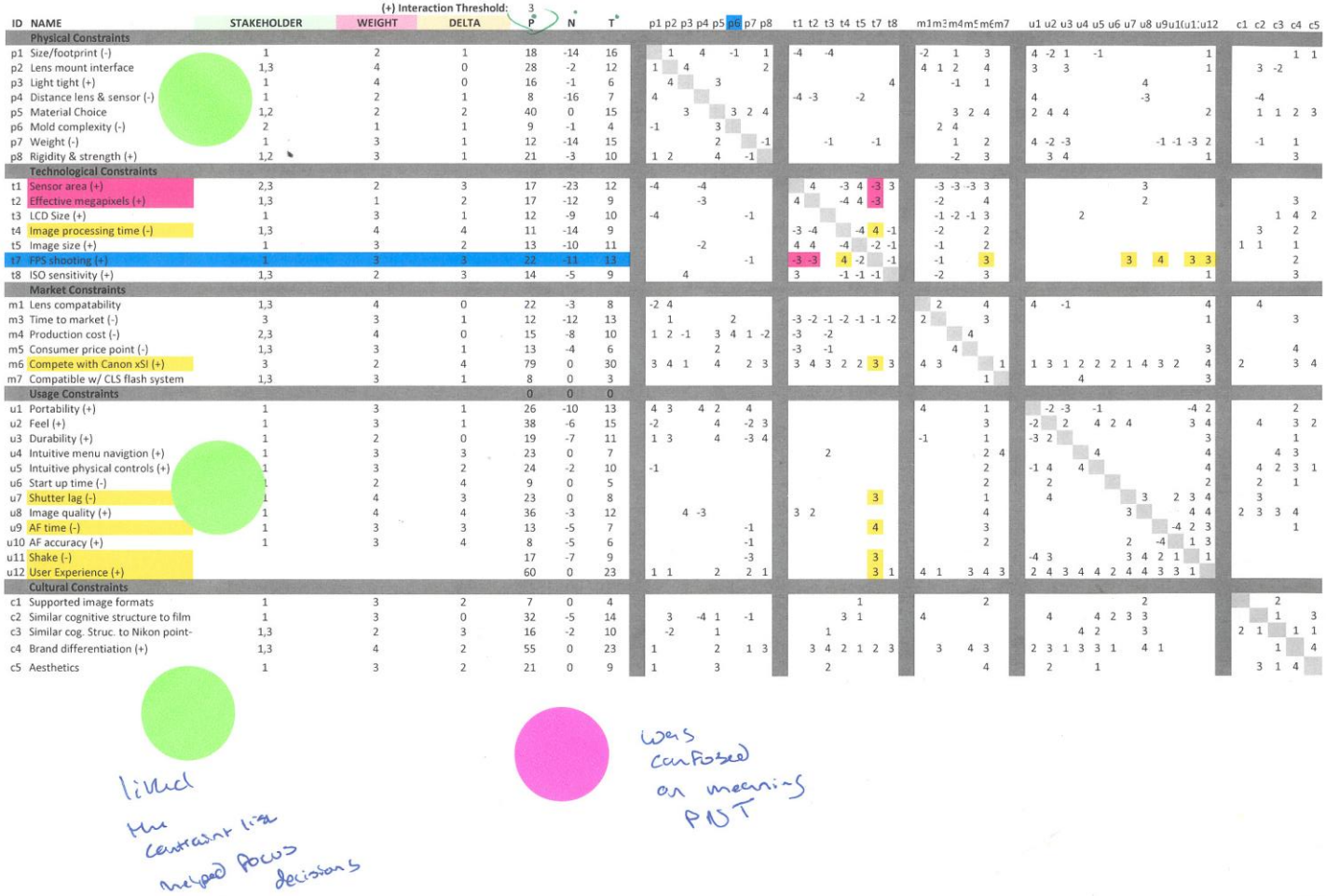


Figure L.1: Like/dislike markup 1.

Figure L.2: Like/dislike markup 2.

Figure L.3: Like/dislike markup 3.

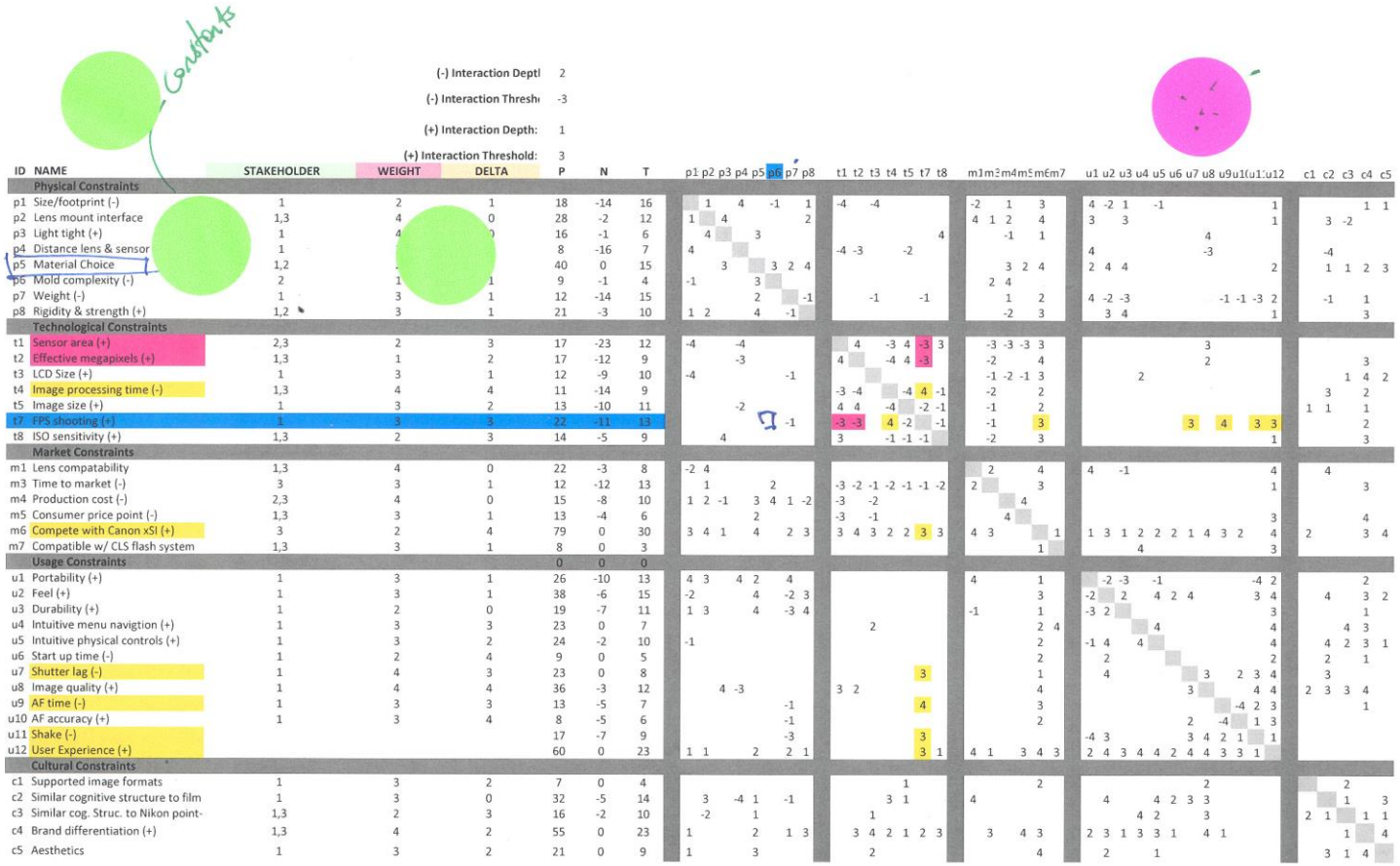


Figure L.4: Like/dislike markup 4.

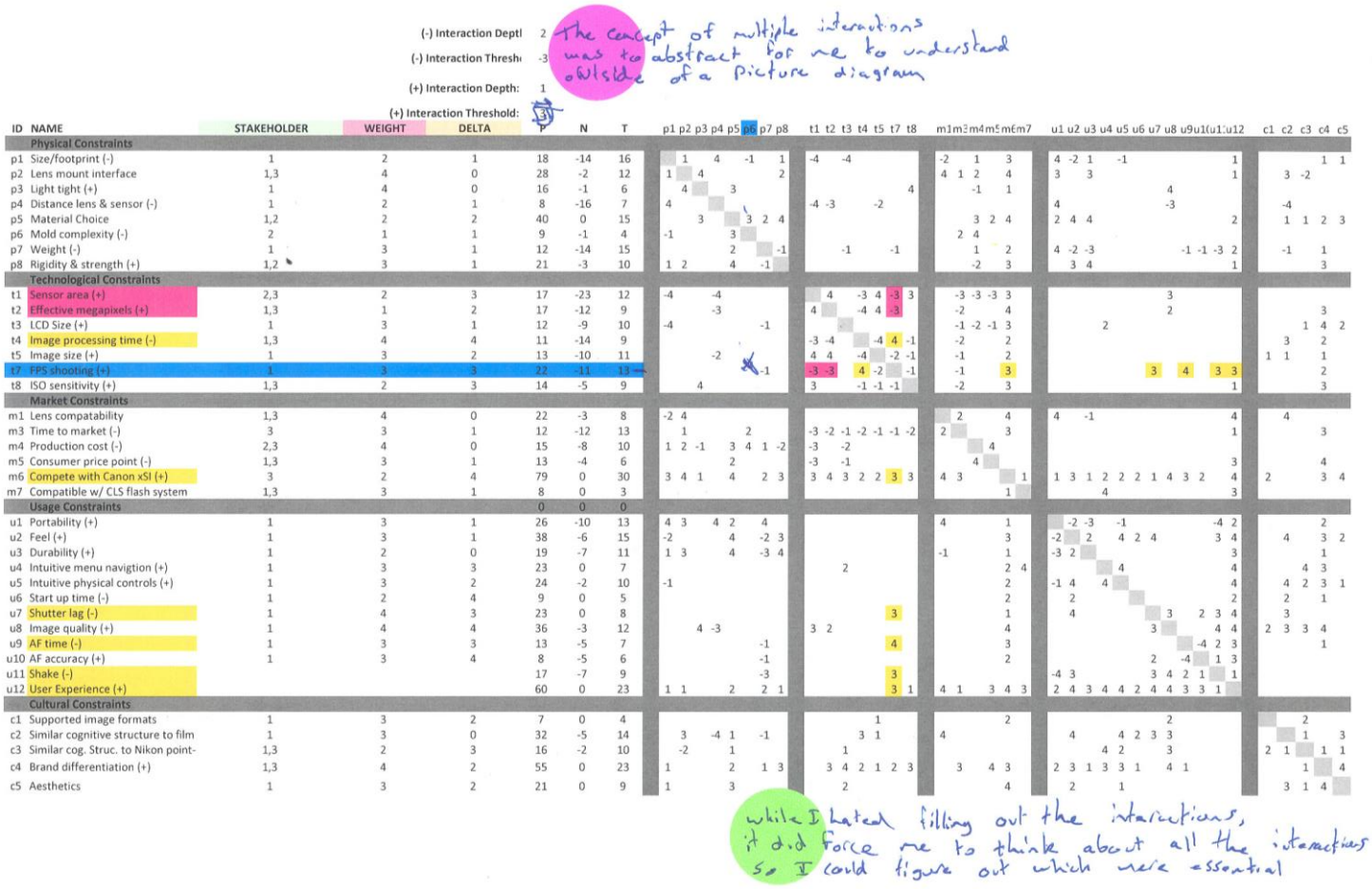


Figure L.5: Like/dislike markup 5.

Figure L.6: Like/dislike markup 6.

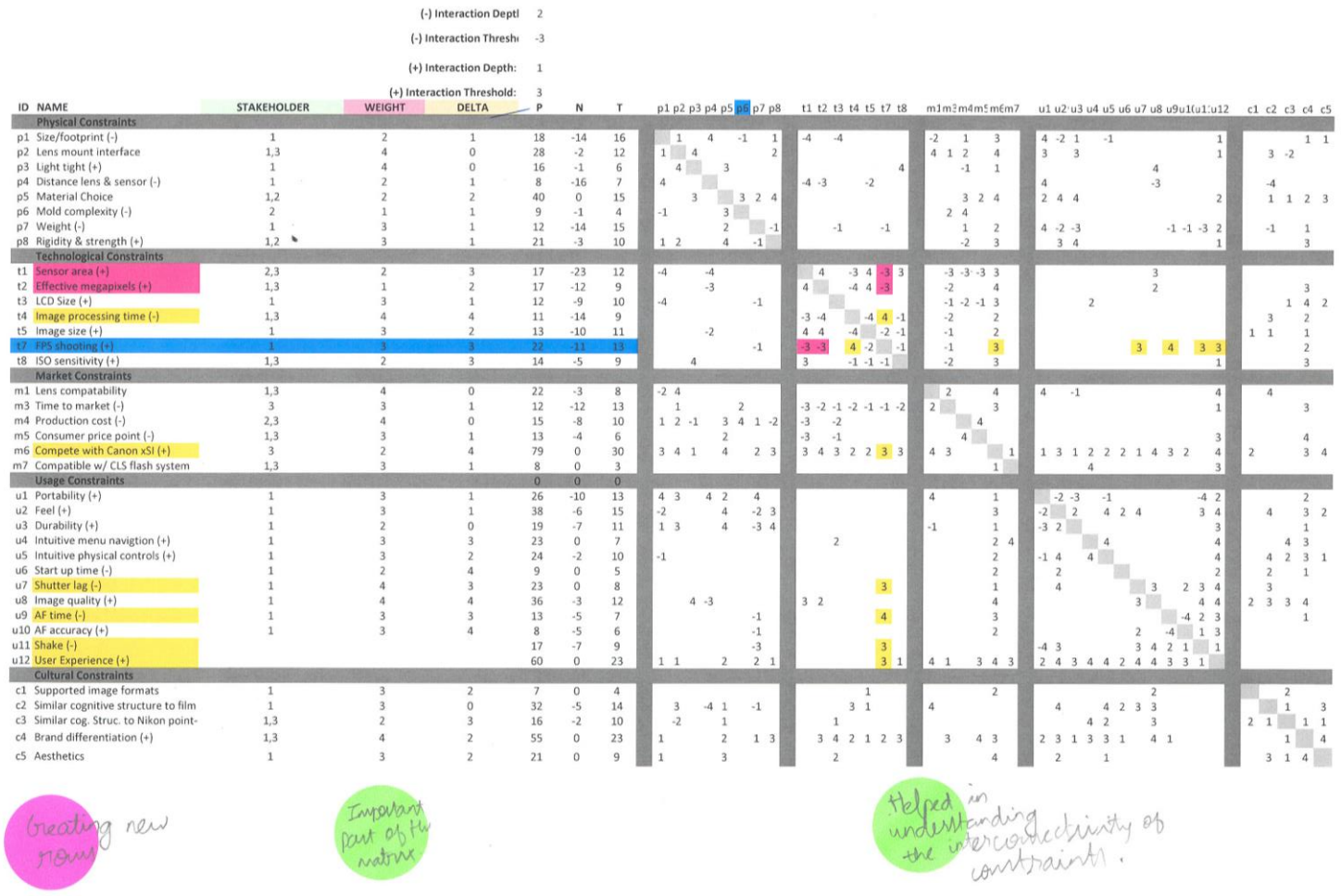


Figure L.7: Like/dislike markup 7.

Figure L.8: Like/dislike markup 8.

Figure L.9: Like/dislike markup 9.

Figure L.10: Like/dislike markup 10.

Figure L.11: Like/dislike markup 11.

Figure L.12: Like/dislike markup 12.

Figure L.13: Like/dislike markup 13.