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**SYSTEM COST BASED MATERIAL SELECTION
FOR ENGINEERING THERMOPLASTICS**

DISSERTATION

**Presented in Partial Fulfillment of the Requirements for
the degree Doctor of Philosophy in the
Graduate School of The Ohio State University**

By

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ABSTRACT

This dissertation describes system cost based material selection, a procedure for considering mechanical requirements, manufacturing costs, and material selection in the design of injection molded engineering thermoplastic parts. The benefit of this approach is the simultaneous consideration of the implications of material selection and part geometry on estimated manufacturing cost during candidate design selection. Using cost as a material selection measure permits the examination of system cost as a function of application requirements.

The current implementation uses the allowable deflection of a flat plate and equivalent system stiffness as performance measures. Manufacturability concerns include required part thickness and gating scheme to adequately mold the part, production costs for meeting part tolerance requirements, and a resulting cycle time based on part cooling time estimates. Part manufacturing cost includes material cost, cycle time, and production costs. Two examples from the desktop printer and automotive markets show the merits of this approach.

Dedicated to my parents

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TABLE OF CONTENTS

	<u>Page</u>
ABSTRACT	ii
ACKNOWLEDGMENTS.....	iv
VITA	vi
FIELDS OF STUDY	vi
TABLE OF CONTENTS	vii
LIST OF FIGURES	x
LIST OF TABLES	xiii
1 INTRODUCTION.....	1
1.1 Background	1
1.2 Material Selection for Injection Molded Plastic Parts.....	2
1.3 Previous Work in Material Selection	3
1.4 Research Approach.....	5
1.5 Target Contributions	6
1.6 Dissertation Outline.....	6
2 THE MATERIAL SELECTION PROBLEM	8
2.1 Introduction	8
2.1.1 The Product Design Process.....	9
2.1.2 Strategic Issues Impacting Material Selection.....	10
2.2 Property Ranking Approaches.....	12
2.2.1 Standard Pruning and Ranking.....	12
2.2.2 A Composite Property Ranking Approach.....	13
2.3 Knowledge-based Approaches	23
2.4 Application-based Approaches.....	26
2.5 Ashby Approach.....	33
2.6 System Performance-based Approach.....	41
3 THERMOPLASTIC MATERIAL TAXONOMY AND BEHAVIOR.....	44
3.1 Introduction	44
3.2 Material Taxonomy	44

3.3 General Properties and Attributes	46
3.3.1 Density.....	46
3.3.2 Cost	47
3.4 Mechanical Behavior.....	47
3.4.1 Stiffness and Strength.....	47
3.4.2 Time, Temperature, and Stress Dependence	49
3.4.3 Impact Behavior	52
3.4.4 Fatigue Behavior	52
3.5 Thermal Properties	53
3.5.1 Thermal Conductivity.....	53
3.5.2 Specific Heat	55
3.6 Dimensional Properties	56
3.6.1 Mold Shrinkage	56
3.6.2 PVT Behavior.....	56
3.7 Other Issues	59
3.7.1 Flammability Ratings	59
3.7.2 Chemical Compatibility	59
4 SYSTEM PERFORMANCE AND PROCESS MODELING	61
4.1 Introduction	61
4.2 Mechanical Performance Models.....	61
4.2.1 Strength	61
4.2.2 Stiffness.....	62
4.2.3 Impact.....	72
4.2.4 Fatigue.....	74
4.3 Processing Cost Drivers	74
4.3.1 Cycle Time	74
4.3.2 Achievable Flow Length	76
4.3.3 System Shrinkage Behavior	77
5 SYSTEM COST BASED MATERIAL SELECTION.....	85
5.1 Introduction	85
5.2 Injection Molding Cost Drivers.....	86
5.2.1 Wall Thickness.....	86
5.2.2 Dimensional Accuracy	86
5.3 Cost as a Material Selection Measure	86
5.4 Mapping Required Tolerance to Cost	88
5.5 Optimizing Material Selection	94
5.5.1 Design Variables	95
5.5.2 Objective Function	95
5.5.3 Equality and Inequality Constraints	96
5.5.4 Solution and Discussion	97

6 APPLICATION: INKJET PRINTER COMPONENTS.....	99
6.1 Introduction	99
6.2 Printer Base	99
6.3 Printer Chassis.....	106
7 APPLICATION: AUTOMOTIVE COMPONENTS	113
7.1 Introduction	113
7.2 HVAC Housing	113
7.3 Battery Pack Housing.....	119
8 DISCUSSION	125
8.1 Introduction	125
8.2 Factors Influencing Material Selection	125
8.2.1 Material Properties	125
8.2.2 System Properties	126
8.3 Implications of the Case Studies	127
8.4 Continuing Challenges	129
9 CONCLUSIONS	131
9.1 Summary	131
9.1.1 The Material Selection Problem.....	131
9.1.2 Existing Material Selection Approaches	131
9.1.3 System Cost Based Material Selection.....	132
9.1.4 Material Selection Case Studies.....	133
9.2 Contributions.....	133
9.3 Future Work	134
REFERENCES.....	136

LIST OF FIGURES

<u>Figure</u>	<u>Page</u>
Figure 1.1: Schematic of the dissertation outline	7
Figure 2.1: The component design process	8
Figure 2.2: GE Select™ material selection screen showing flame retardant and UV stabilized grades with a flexural modulus greater than a certain threshold.....	13
Figure 2.3: Material property preference input for HyperQ/Plastics (Beiter, 1992)	16
Figure 2.4: Flat plate and prescribed conditions for the Ashby example.....	36
Figure 2.5: Young's Modulus vs. relative cost per unit volume from Ashby	38
Figure 2.6: An approach to systematic material selection.....	43
Figure 3.1: Material Taxonomy for system cost-based material selection.....	45
Figure 3.2: General tensile stress-strain curve for a filled and unfilled thermoplastic	48
Figure 3.3: 3-point bend test (left) and 4-point bend test (right) for flexural modulus....	49
Figure 3.4: Deflection temperature under load (DTUL) testing apparatus (Malloy, 1994).....	50
Figure 3.5: Deflection under load temperature as a function of cost	50
Figure 3.6: Strain versus time for a filled PC and unfilled ABS polymer	51
Figure 3.7: Izod test configuration (Trantina, et al., 1994)	52
Figure 3.8: Applied stress vs. cycles to failure for an ABS and PC.....	53
Figure 3.9: Thermal conductivity is the rate heat is conducted through a solid (Ashby, 1992).....	54
Figure 3.10: Thermal conductivity as a function of temperature	54

Figure 3.11: Specific heat as a function of temperature	55
Figure 3.12: PVT diagram for an amorphous polymer	57
Figure 3.13: PVT diagram for a semi-crystalline polymer.....	57
Figure 4.1: Stress vs. strain for polycarbonate (GF10%) at various temperatures and strain rates.....	62
Figure 4.2: Uniform Loading of a Flat Plate with Clamped Edges.....	64
Figure 4.3: Part thickness vs. allowable deflection for an ABS and PC	65
Figure 4.4: Ribbed plate and flat plate geometry	66
Figure 4.5: Effective modulus as a function of temperature	71
Figure 4.6: Required part thickness as a function of temperature for selected thermoplastics.....	72
Figure 4.7: Flat plate with rib under impact load P	73
Figure 4.8: Maximum principal stress to yield stress as a function of fillet radius r and plate thickness h	73
Figure 4.9: Flat plate geometry for cooling calculations.....	75
Figure 4.10: Cooling time as a function of wall thickness for selected thermoplastics ...	76
Figure 4.11: Achievable flow length as a function of wall thickness	77
Figure 4.12: PVT diagram with molding process trace.....	79
Figure 4.13: Linear shrinkage as a function of packing pressure	80
Figure 4.14: Linear shrinkage as a function of melt temperature.....	81
Figure 4.15: Linear shrinkage as a function of mold temperature	82
Figure 4.16: Linear shrinkage as a function of gate size.....	83
Figure 5.1: Normalized material cost as a function of application temperature	88
Figure 5.2: Machine–Labor rate as a function of desired tolerance	91
Figure 5.3: Part cost as a function of required tolerance.....	94

Figure 6.1: Printer base	100
Figure 6.2: Flat plate model and loading for the printer base	101
Figure 6.3: Cost as a function of temperature for the printer base	102
Figure 6.4: Cost as a function of creep test time for the printer base.....	103
Figure 6.5: Cost as a function of required tolerance for the printer base	104
Figure 6.6: Cost as a function of application temperature, including high impact polystyrene.....	105
Figure 6.7: Printer chassis	107
Figure 6.8: Normalized cost as a function of temperature for the printer chassis.....	109
Figure 6.9: Normalized cost as a function of creep time for the printer chassis	110
Figure 6.10: Normalized cost as a function of required tolerance for the printer chassis.....	111
Figure 7.1: HVAC system.....	114
Figure 7.2: Cost as a function of temperature for the HVAC housing.....	116
Figure 7.3: Cost as a function of creep test time for the HVAC housing	117
Figure 7.4: Cost as a function of required tolerance for the HVAC housing	118
Figure 7.5: Five-sided box model and loading for the battery pack housing	120
Figure 7.6: Cost as a function of application temperature for the battery pack housing	121
Figure 7.7: Cost as a function of tested creep time for the battery pack housing	122
Figure 7.8: Cost as a function of required tolerance for the battery pack housing.....	123

LIST OF TABLES

<u>Table</u>	<u>Page</u>
Table 2.1: Ranking of several hypothetical materials using Equation 2.5	17
Table 2.2: Ranking of several hypothetical materials using Equation 2.7	19
Table 2.3: Ranking of several hypothetical materials using Equation 2.12	20
Table 2.4: Ranking of several hypothetical materials using Equation 2.13	21
Table 2.5: Ranking of several hypothetical materials using the multiplicative scoring scheme (Equation 2.14).....	22
Table 2.6: Ranking of several hypothetical materials using the product-exponential scoring scheme (Equation 2.15)	22
Table 2.7: Performance Factors and Criteria used in Nielson, et al. (1986)	24
Table 2.8: Application profiles from Richards (1995)	27
Table 2.9: Material properties considered by Richards (1995)	28
Table 2.10: Design dependent considerations from Richards (1995)	29
Table 2.11: Application profile (design requirements) for a desktop computer housing.	30
Table 2.12: Desktop computer housing material selection results	31
Table 2.13: Material properties considered by Ashby	34
Table 2.14: Design limiting material properties.....	35
Table 2.15: Ashby performance indices for minimum weight, cost, or energy	35
Table 2.16: Materials with the best stiffness-to-cost performance for the flat plate example	39
Table 3.1: Selected general polymer class property ranges and cost.....	46

Table 3.2: Resistance of selected polymer families to specific chemicals (Domininghaus, 1988 [§]).....	60
Table 4.1: Constants α and β_1 for various values of a/b (Young, 1989)	64
Table 5.1: Process deviations for standard and fine tolerance molding processes [£]	90
Table 5.2: Standard and fine tolerance machine–labor rates (\$/hr).....	90
Table 5.3: Mechanical and Manufacturing Performance Models	98
Table 6.1: Printer base current design	100
Table 6.2: Material selection summary for the printer base	106
Table 6.3: Printer chassis current material selection.	107
Table 6.4: Material selection summary for the printer chassis.....	112
Table 7.1: HVAC housing current design	114
Table 7.2: Material selection summary for the HVAC housing.....	119
Table 7.3: Battery pack housing design requirements.....	119
Table 7.4: Material selection summary for the battery pack housing.....	124
Table 9.1: Summary of implications of the material selection case studies.....	133

CHAPTER 1

INTRODUCTION

1.1 Background

Injection molding is a powerful and comprehensive manufacturing process. However, it can also be complicated and costly. The designer must consider not only part performance requirements, but process and material constraints as well. Effective management of these constraints in a time-efficient manner can yield significant product cost savings and a quick time-to-market.

A designer would like to arrive at the optimum solution in the shortest time possible. An optimum solution should contain the material, process, and geometry specification that meets the functional requirements at the lowest component cost. In this rough definition, I am ignoring what might be called the optimal *system* cost, as well as what I mean by “meets the functional requirements”.

Currently, the designer has several levels of knowledge available. In the early stages of design, and throughout much of the design process, the designer can employ qualitative knowledge in the form of personal experience and tabulated rules of thumb. After the design has been detailed, the designer can use FEM to assess mechanical and

thermal performance, and process simulation to reveal processing trouble-spots with the design.

Unfortunately, FEM and process simulation require detailed geometric, process, and material information. The need for this specialized information is understandable, since the polymer process numerical model is complex. This level of detail is usually available only further into the design process, at which point the designer is less willing or able to make major changes. When the tools are used in this manner, the nature of the solution becomes much less iterative, and more a “band-aid” change.

The designer needs process models and knowledge that fill in the gap between rules-of-thumb and detailed FEM or process simulation analysis. The less detail known about a design, the less complex and accurate any mechanical or process model can be, *however simplified mechanical and manufacturing performance models can be extremely effective in capturing the coupled effects of geometry, process, and material properties. Such an approach can lead to a more suitable set of candidate materials, based on a relative cost index, resulting in a lower overall component cost.*

1.2 Material Selection for Injection Molded Plastic Parts

Traditionally, designers consider part performance requirements in narrowing down, or *pruning*, a set of candidate materials. Typical selection criteria include material cost, stiffness, creep, impact and fatigue resistance, service temperature, chemical and UV

resistance, hardness or abrasion resistance, regulation compatibility (e.g., flame retardance or FDA approval), flow characteristics, and surface finish.

Quantitative pruning of candidate materials occurs on several levels. For instance, aesthetic, regulation, and service environment requirements can immediately eliminate certain materials. Mechanical, thermal, cost, and processing property requirements will narrow the search even further, based on more detailed structural and process analyses. For critical applications, or for part requirements for which no adequate predictive models may exist, engineers must often resort to prototype and testing to arrive at a final material choice.

The preceding scenario for plastic material selection assumes that time, knowledge, and capital resources are available at sufficient levels throughout the design process. *However, compressed lead times, unavailable material property data, unfamiliarity with application-specific material behavior, and uncertainty regarding the interaction between geometry, material, and process will often lead to non-optimal material selection.*

1.3 Previous Work in Material Selection

As material vendors introduce more types of plastics to meet specialized needs, effective material selection becomes increasingly important. One way of accommodating qualitative requirements in a materials selection database is to use rule-based inference. Dixon's work on GERES (Nielsen, 1986) adds a knowledge-based approach to GE's

engineering database. This pilot program uses IF-THEN rules to categorize the candidate set of materials to match the user's needs. This feature accommodates qualitative rules related to the specific usage for which the materials are designed. GERES incorporates both quantitative and qualitative knowledge about plastic materials obtained from a group of plastics experts at GE plastics. Beiter, et al. (1991) describe a procedure for selecting a polymer based on a weighted sum of material property preferences. Ashby (1992) describes a procedure for material selection based on an objective function for design attributes such as weight, cost, strength and stiffness. The objective function leads to a material performance index, which he uses to select a material. Oehler, et al. (1994) discuss integrating basic requirements (UV resistance, flammability rating), loading, and manufacturing constraints into material selection.

The above approaches suffer from one or more of the following shortcomings:

- 1) They do not explicitly capture the fact that material properties and geometry can be combined in different manners to meet the same required system properties (e.g., stiffness as a *system* property, rather than a *material* property).
- 2) They do not explicitly consider the effect that processing may have on system properties (e.g., orthotropic effects, level of packing pressure and material shrinkage rates on system shrinkage).
- 3) They do not map system (material, geometry, process) performance to a comparative scale.

1.4 Research Approach

This dissertation proposes a material selection methodology that utilizes simplified models of mechanical, process, and geometry in conjunction with material properties to map the cost of meeting system performance requirements to a single relative scale.

Major issues include:

- 1) *Part stiffness*: allowable deflection of a flat plate or other simple geometries will determine a wall thickness. This model will also incorporate time and temperature effects, orthotropic effects (distinct flow and cross-flow moduli) in the case of fiber-filled materials, and the effect of ribbed patterns on system stiffness.
- 2) *Impact strength*: minimum radius on ribbed plates to ensure ductile (not catastrophic) failure.
- 3) *Fatigue strength*: cyclic loading conditions with a known stress magnitude can yield a cycles-to-failure estimate.
- 4) *Shrinkage*: system shrinkage response (the combined effect of material PVT behavior and processing variable levels) will place limits on achievable geometric tolerances.
- 5) *Cooling time*: the largest component of cycle time, is strongly dependent on wall thickness, and, to a lesser extent, on material properties.
- 6) *Flow length*: wall thickness can also be constrained by achievable flow length. High-strength materials may allow thinner wall sections, but can inhibit part fillability.

To incorporate material selection on a uniform scale, this dissertation also considers:

- 1) *System cost*. Cost appears to be the most natural objective function scale on which to compare two or more materials. However, for useful material candidate ranking, the wide array of design variables pertaining to geometry and process must appear in the objective function, and the mapping of each design variable set to cost must be order-preserving.
- 2) *Optimization*. With the development of a proper cost scale (the objective function), it is mathematically possible to optimize material, geometry, and process window (the design variables). Optimization, however, will be subject to the limitations of the performance models and my application of them.

1.5 Target Contributions

- 1) Systematic approach to selecting the optimum plastic material for a given set of prescribed mechanical requirements.
- 2) A computer decision support tool that incorporates the phenomenological models in conjunction with the material property database necessary to perform the above-mentioned analysis.
- 3) Insight into the role that the interaction between material properties and geometry has on the relative ranking of suitable materials.
- 4) A framework for using mechanical and manufacturing performance models to conduct material and process selection.

1.6 Dissertation Outline

This dissertation develops an engineering thermoplastic selection procedure for structural components that incorporates *system* properties—material properties, part

geometry, and processing requirements. Chapter 2 describes the material selection problem in more detail, reviewing previous work and introducing the need for the performance-based approach. Chapter 3 details the polymer material classes, properties, and physical behavior that this dissertation includes. The next two chapters describe the performance-based approach in more detail; Chapter 4 describes system performance and process modeling, and Chapter 5 introduces the material selection cost model. In Chapter 6 and 7, several application examples show the effectiveness of the approach. Chapter 8 discusses the results of the dissertation, and Chapter 9 finishes with conclusions and directions for future work. Figure 1.1 shows a schematic of the dissertation outline.

Figure 1.1: Schematic of the dissertation outline

CHAPTER 2

THE MATERIAL SELECTION PROBLEM

2.1 Introduction

The material selection problem is really one of design; that is, how does a designer meet multiple design objectives—strength, stiffness, durability, low-cost, light-weight, etc.—with virtually limitless choices of material, process, and geometry?

Figure 2.1: The component design process

Ideally, designers would like to optimize the tradeoffs between product function, part geometry, material selection, manufacturing process, and cost. Effective component design is an iterative process requiring timely input from many sources, including product engineers, tooling engineers, process and material engineers, cost accountants, production

and marketing personnel, textbooks, structural analysis, process simulation, and prototype results. And this is not an exhaustive list.

This chapter reviews the material selection problem in more detail. The first section places the material selection problem in the context of the design process. Then, current approaches to the material selection problem are reviewed. The chapter finishes by introducing the system cost-based approach to material selection.

2.1.1 The Product Design Process

While this dissertation focuses on material selection for thermoplastic components, a systematic material selection methodology must accommodate the broader design process. In this light, we present the following as a high-level view of the product design process, highlighting material selection issues:

- 1) *Generation of concept alternatives.* This phase of product design requires some level of understanding of material behavior and manufacturing processes. The geometry at this stage is rough or primitive, allowing for simple closed form solutions for performance analysis. Material data at this stage covers basic mechanical, thermal, and physical properties, and may be considered on the class level—for instance, engineering alloys, polymers, composites, ceramics, etc. Engineers can apply knowledge of high-level processing and material property constraints at this stage to eliminate obvious non-optimum concepts.
- 2) *Comparing alternatives and selecting the optimum design.* This stage of the product design process incorporates more detailed process and material data. Design geometry at this stage is still simple—supporting closed-form performance and processing analyses for trade-off

- 3) *Performing detailed design.* This phase incorporates such tools as finite element analyses and process simulation, both of which require detailed geometry information and material data. Due to the time-intensive nature of these analyses, the number of design candidates is typically very small.
- 4) *Prototype and testing.* This stage of the design process is costly in terms of time and money. While this stage is not always performed, it does permit fine-tuning of geometry and material to meet performance and processing requirements, especially for high-margin or cutting-edge products.

2.1.2 Strategic Issues Impacting Material Selection

Material selection also includes other issues that do not necessarily follow the generalized design process listed above. The list below contains several issues that impact material selection below, though by no means is this an exhaustive set:

- 1) *Evolutionary material selection.* In most cases, component design does not start from scratch. Previous component designs of similar applications offer a wealth of knowledge that leverages the current design task—material selection, process choice, and geometry configuration. In-house design projects undergoing redesign often provide knowledge of known weaknesses that can be solved with slight improvements in geometry or material choice. Similarly, competitive product bench-marking can provide insight into current state-of-the-art material and process choices and provide a starting point for the material selection problem.
- 2) *In-house expertise.* In some corporations, product history and personnel experience dictate the choice of materials and processes. This does not necessarily lead to higher-cost designs since in-house expertise can facilitate

expedient geometry and process design, less rework, and quicker time-to-market.

- 3) *Corporate buying contracts.* Purchasing material quantities in bulk can sometimes provide significant cost savings. This may result in over-engineered components, but over time can provide detailed knowledge of the mechanical and processing performance of a particular material.
- 4) *System design issues.* On a system-design level, efforts to reduce material variety in a product may dictate material choice. Examples include reduction of material inventory, maintaining aesthetic requirements of integrated design components, and product recycling efforts that seek to improve system material compatibility.
- 5) *Secondary materials and processes.* Secondary processes can often play a role in material selection. Some system application requirements can be met more cost-effectively by considering a combination of materials and processes than by using a single material and process.

Existing systematic approaches to the material selection problem fall roughly into four categories, listed briefly below. The next four sections explain these approaches in more detail.

- 1) *Property ranking approaches.* This approach provides a means for pruning materials based on high-level physical requirements and ranking materials on one or more material property values. This function is usually provided by material vendors in databases that feature materials of a particular class (e.g., engineering plastics, aluminum alloys, etc.).
- 2) *Knowledge-based approaches.* These systems codify materials application experts' knowledge in a computer program. The inputs include a wide array of

application requirements and internal scoring mechanisms to rank a set of materials.

- 3) *Application-based approaches.* These methods seek to leverage prior experience of product applications to quickly prune the material selection problem. This approach can provide a good starting point for material selection and can also serve an educational need, but often limits the user to applications about which the system has knowledge.
- 4) *System performance-based approaches.* These approaches provide a means for assessing material performance using simplified geometry and mechanical, thermal, and processing models. A performance-based approach still orders materials based on some user-indicated criteria, but the ordering is presumed to be more useful since the ordering mechanism is based on two or more material properties combined with (simplified) physical laws. As we will see, the Ashby approach (Ashby, 1992) and the material selection methodology outlined in this dissertation are examples of performance-based approaches.

2.2 Property Ranking Approaches

2.2.1 Standard Pruning and Ranking

Most material databases supplied by material vendors or material database houses provide a means for ranking materials based on a particular material property and pruning this list based on minimum property requirements or particular material attribute (UL listing, UV stabilized, etc.). Figure 2.2 shows an example of a computerized database which performs this function.

	LEXAN	503	PC	✓	✓	3445
	LEXAN	503R	PC	✓	✓	3445
	LEXAN	FL913	PC	✓	✓	3514
	LEXAN	FL933	PC	✓	✓	6890
	VALOX	420SE0U	PBT	✓	✓	7579
	VALOX	553U	PBT+PC	✓	✓	6890

Figure 2.2: GE Select™ material selection screen showing flame retardant and UV stabilized grades with a flexural modulus greater than a certain threshold

2.2.2 A Composite Property Ranking Approach

Beiter, et al. (1991) describe a procedure for selecting a polymer based on a weighted sum of material property preferences. The measure provides a means of “ranking” plastic materials based on the values of multiple properties. The description of the measure that they employ follows.

The authors apply a qualitative ranking procedure to a set of candidate materials that satisfy certain quantitative constraints (e.g., minimum or maximum values of modulus, density, impact strength, etc.). This procedure ranks the pool of materials by the relative importance of several properties. This ranking is accomplished by assigning a normalized “weight” to each property and then computing an aggregate score for each material based

on the weights and normalized values of each property. This procedure is mathematically expressed by the following: let each material in the database be given as x_i , let the property value of a given plastic material be given as $\hat{e}_k(x_i)$, and let the relative importance, or weight, of each property be given as c_k , where c_k is defined over the interval from zero to one, i.e.,

$$c_k \in [0,1] \quad (2.1)$$

Since the aggregate score is concerned only with relative importance between properties, normalize the weights, i.e.:

$$\tilde{c}_k = \frac{c_k}{\sum_{j=1}^m c_j} \quad (2.2)$$

where at least one c_j is not zero. Now, since the resulting aggregate score must have relative meaning, the actual material property values are normalized for each property. Defining the maximum and minimum values of a given property over all the materials to be, respectively:

$$\begin{aligned} \hat{e}_{k(\max)} &= \max_i [\hat{e}_k(x_i)] \\ \hat{e}_{k(\min)} &= \min_i [\hat{e}_k(x_i)] \end{aligned} \quad (2.3)$$

the normalized value of that property for material x_i is:

$$\tilde{e}_k = \frac{\hat{e}_k(x_i) - \hat{e}_{k(\min)}}{\hat{e}_{k(\max)} - \hat{e}_{k(\min)}} \quad (2.4)$$

The score for material x_i , defined as $S(x_i)$, is then given as:

$$\text{Score}(x_i) = S(x_i) = \sum_{k=1}^m \tilde{e}_k(x_i) \cdot \tilde{c}_k \quad (2.5)$$

where $S(x_i) \in [0,1]$. Applying this evaluation function to each material in the candidate generates a ranked list of materials that greater reflects the designer's needs. Also, by way of background, the designer indicates a "preference" (or weight) for a given material property by entering a value from 0 to 100 for any material property of interest.

Critique

Leaving aside questions of whether or not material properties can be sufficiently characterized by a single quantity (e.g., the authors have neglected time and temperature dependence on strength and impact property values), the first thing to examine is the meaning that the authors attached to the *score* (Equation 2.5). The authors stated in the paper that the computed score represented a means of *ranking* the materials based on a multi-property function. For this to be true, the scoring function must preserve order, i.e., Equation 2.6 must preserve order:

$$\text{Score}(x_i) = S(x_i) = \sum_{k=1}^m \tilde{e}_k(x_i) \cdot \tilde{c}_k \quad (2.6)$$

The $\hat{e}_k$'s preserve order, since Equation 2.4 maps the range of property values $\hat{e}_k$ for each material x_i to the interval [0,1]. By the same argument, the normalized weights $\hat{c}_k$ preserve order. It is *not* clear that the sum of normalized weight-property value products (Equation 2.6) preserves order.

Property	Relative Importance (Lower to Higher)	Percentage
High Tensile Strength	[Slider]	84 %
High Impact Strength	[Slider]	72 %
High Temperature Strength	[Slider]	31 %
Low Density	[Slider]	39 %
High stiffness	[Slider]	77 %
Low Cost	[Slider]	94 %
UL 94 Flammability Rating	(HB) (V-2) (V-1) (V-0) (5V)	
Colorable		
UV Stabilized		

Buttons: Main Menu, Quantitative, Application, Advise

Figure 2.3: Material property preference input for HyperQ/Plastics (Beiter, 1992)

Even more unclear is the quantity that the authors are trying to measure. They labeled the slide controls on an input card “relative importance” (Figure 2.3). For instance, if you wanted to indicate that tensile strength is twice as important as impact strength, then indicate twice as much weight. This is, however, *not* true. It is valid to say

that the weight can capture an order preference. But, the intent of the weights is to reveal materials with properties that might match the designer's requirements, so the weighting requires more than just an ordering of preferences to sift out the desired materials.

I performed several what-if scenarios to determine if the score (as defined) will produce any strange results. Table 2.1 contains some sample materials and property values, as well as a resulting score. The materials have closely grouped values of tensile strength, and widely varying impact strength. For equally weighted property preferences (in this case 100), you would expect the score to rank the materials very closely with the impact strength. However, the score *penalizes* a material for having the lowest value of a property ($\tilde{e}_k = 0$). So, in this case, material A (with the highest tensile strength, but only slightly so) scores higher than material E (which has the lowest tensile strength, but only slightly lower than A's), even though material A has by far a much lower impact strength than material E. So the score, as defined, does not preserve order in the sense that one might expect.

Table 2.1: Ranking of several hypothetical materials using Equation 2.5

Material	Tensile Strength (ksi)	Impact Strength (ft-lb/in)	Score	Rank
A	2301	5.0	0.538461	3
B	2300	17.0	0.750000	1
C	2300	16.5	0.730769	2
D	2300	4.0	0.250000	5
E	2299	16.8	0.492308	4

In a well populated database, with broader distributions of property values, this deficiency may not surface. Nonetheless, the score does not preserve order. This can be

corrected by redefining the $\tilde{e}_k$'s (normalized property values) in such a way that the materials with a maximum or minimum property value do not skew the score. Two possible alternatives include redefining $\tilde{e}_k$ as:

$$\tilde{e}_k = \frac{\hat{e}_k(x_i)}{\hat{e}_{k(\max)}} \quad (2.7)$$

or

$$\tilde{e}_k = \frac{\hat{e}_k(x_i) - \hat{e}_{k(\min)}}{\hat{e}_{k(\max)} - \hat{e}_{k(\min)}} \quad (2.8)$$

where

$$\begin{aligned} \hat{e}_{k(\max)} &= 1.1 \left\{ \max_i [\hat{e}_k(x_i)] \right\} \\ \hat{e}_{k(\min)} &= 0.9 \left\{ \min_i [\hat{e}_k(x_i)] \right\} \end{aligned} \quad (2.9)$$

Using Equation 2.7 will compensate for property values that are closely packed together (producing closely packed $\tilde{e}_k$'s), while Equation 2.8 will merely prevent an $\tilde{e}_k$ from evaluating to zero or one. Table 2.2 shows the same hypothetical materials, only now using the scoring mechanism of Equation 2.7.

Table 2.2: Ranking of several hypothetical materials using Equation 2.7

A	2301	5.0	0.647059	4
B	2300	17.0	0.999782	1
C	2300	16.5	0.985076	3
D	2300	4.0	0.617429	5
E	2299	16.8	0.993683	2

We are still left with the question of what the relative magnitude of the assigned property weights actually means. It appears to only induce a particular ordering of the materials while not preserving any interval meaning (nor could it, since we are reducing n dimensions to one measure).

Implications of the Normalization Procedure

The material selection routine uses normalized material property values to calculate a preference-based score. Equation 2.10, the original normalization procedure, and Equation 2.11, the proposed normalization procedure, are (again) listed below:

$$\tilde{e}_k = \frac{\hat{e}_k(x_i) - \hat{e}_{k(\min)}}{\hat{e}_{k(\max)} - \hat{e}_{k(\min)}} \quad (2.10)$$

$$\tilde{e}_k = \frac{\hat{e}_k(x_i)}{\hat{e}_{k(\max)}} \quad (2.11)$$

Equation 2.10 is an interval-like transformation, which preserves relative differences between values of a given property. This normalization scheme may be useful for situations in which property values may be negative, but this analysis does not address this. However, this transformation can yield “0” values (when $\hat{e}_k(x_i) = \hat{e}_{k(\min)}$) for $\tilde{e}_k$.

which does not make it very useful for preference schemes (listed below). Equation 2.11 is a ratio scale (preserves interval and scale) which makes it useful for various preference schemes.

Alternative Preference Schemes

I have prepared a set of hypothetical materials with equivalent tensile strength values and various impact strength values (as listed in Table 3) to compare four different material preference schemes. Each of these schemes uses the property value normalization procedure described in Equation (7) above and yields a preference based on a combination of the normalized property values and the user-assigned property weights (tensile strength and impact strength both have equal preferences in this case).

Current Scheme:

$$\text{Score}(x_i) = S(x_i) = \sum_{k=1}^m \tilde{e}_k(x_i) \cdot \tilde{c}_k \quad (2.12)$$

In this scheme, the score is the weighted sum of the normalized property values. As shown in Table 2.3, the score preserves order.

Table 2.3: Ranking of several hypothetical materials using Equation 2.12

Material	Tensile Strength (ksi)	Impact Strength (ft-lb/in)	Normalized Tensile Strength	Normalized Impact Strength	Rank
A	2300	10	1.00	1.00	1
B	2300	8	0.90	0.80	2
C	2300	5	0.75	0.50	3
D	2300	2	0.60	0.20	4
E	2300	1	0.55	0.10	5

Lexicographic Scheme:

$$xy \succ x'y' \text{ if either } x > x' \text{ or } x = x' \text{ and } y \geq y' \quad (2.13)$$

In this scheme, the materials are ranked based on lexicographic order of individual concatenated property values ($xyz\cdots$). Table 2.4 shows hypothetical results. Two immediate problems arise: (1) How do you include the relative magnitude of the property preferences? and (2) In the simple lexicographic scheme implemented, the results don't preserve order in the sense that might be expected (i.e., one would still expect material A to be most desirable).

Table 2.4: Ranking of several hypothetical materials using Equation 2.13

Material	Property 1	Property 2	Property 3
A	2299	10	5
B	2300	8	1
C	2300	5	2
D	2300	2	3
E	2300	0	4

Multiplicative Scheme:

$$\text{Score}(x_i) = S(x_i) = \prod_{k=1}^n \tilde{e}_k(x_i) \cdot \tilde{c}_k \quad (2.14)$$

where

$$\tilde{e}_k(x_i) \cdot \tilde{c}_k \equiv 1 \text{ if } \tilde{c}_k = 0 \quad (2.15)$$

In this scheme, the score is the weighted *product* of the normalized property values. The resulting score *can* preserve order (and even scale, in this simplified case, although it won't in general). However, this score will have a problem if any $\tilde{e}_k(x_i) = 0$.

Table 2.5: Ranking of several hypothetical materials using the multiplicative scoring scheme (Equation 2.14)

Material	Temperature	Strength	Stiffness	Rank
A	2300	10	0.250	1
B	2300	8	0.200	2
C	2300	5	0.125	3
D	2300	2	0.050	4
E	2300	1	0.025	5

Product-Exponential Scheme:

$$\text{Score}(x_i) = S(x_i) = \prod_{k=1}^n [\tilde{e}_k(x_i)]^{c_k} \quad (2.16)$$

In this scheme, the score is the exponentially-weighted product of the normalized property values. The resulting score preserves order.

Table 2.6: Ranking of several hypothetical materials using the product-exponential scoring scheme (Equation 2.15)

Material	Temperature	Strength	Stiffness	Rank
A	2300	10	1.000000	1
B	2300	8	0.894427	2
C	2300	5	0.707107	3
D	2300	2	0.447214	4
E	2300	1	0.316228	5

Conclusion

The intent of the material score is to order a list of materials based on a material's property value and user-assigned property weights. A ranking mechanism which preserves order is a minimum requirement. It is not clear that an interval- or ratio-preserving scale is required, nor is it even clear that it could be proven that one exists, since any ranking procedure applied necessarily maps multiple values to a single value.

In summary, the benefit of property ranking approaches is that they allow the user to quickly examine the range of material property values for a given material. Perhaps the most useful function of property ranking approaches (those attached to databases) is that they provide somewhat detailed information about materials (at least the good databases). However, these approaches are limited in that they don't provide a systematic method of choosing a material for a particular application, unless the designer knows exactly the material properties needed. Beiter, et al., (1992) attempt to provide a ranking mechanism that permits multi-property material ordering, but this ranking mechanism is questionable since the material property preferences do not seem to have practical meaning, and don't necessarily result in an ordered list of materials.

2.3 Knowledge-based Approaches

Over the years there have been many material selection systems proposed in the literature (Nielson, et al, 1986; Wiggins, 1986; Lovrich, et al., 1986; Jong, et al., 1989), primarily of a computerized nature. These systems use quantitative (tensile strength,

modulus, impact strength, etc.) and qualitative (flammability, transparency and color, UV stability, etc.) material information, as well as quantitative and qualitative *application requirements* elicited from the user. The method by which these approaches use the application requirements to prune and rank materials is their primary difference.

Table 2.7: Performance Factors and Criteria used in Nielson, et al. (1986)

Flammability	Not specified							
Low Temperature	Not specified							
Impact Strength [ft-lbs/in]	normal notched > 1 unnotched > 1	high notched > 5 unnotched > 5	very high notched > 5 unnotched > 15	very high w/stress notched > 15 unnotched > 15	conc.	extremely high notched > 15 unnotched > 40		
Elevated Temperature [°F]	room temperature	< 125	< 160	< 200	< 250	< 300	< 350	< 400
Transparency and Color	Not specified							
UV Stability	Not specified							
Strength	normal service and light loads	slightly stronger material than the first criteria		Heavy, concentrated loads		Maximize strength		
Stiffness and Deflection [psi]	normal service @200°F $E_{eff}>150000$	appl. where rigidity is a consideration $E_{eff}>300000$		minimize DUL and rigidity $E_{eff}>500000$		minimize DUL is driving factor $E_{eff}>800000$		exceptional stiffness $E_{eff}>1100000$
U.L Electrical/Temp	Not specified							
Moisture & Chemical Compatibility	moisture	weak acids	strong organic acids	strong mineral acids	concentrated oxidizing acids	weak alkalies	strong alkalies	
Agency Approvals	FDA				National Sanitation Foundation			

A well known example is the integration of a knowledge-based approach and GE Plastics resin database by Nielson, et al. (1986), called GERES. Their approach uses material performance *factors* and *criteria*, listed below in Table 2.7. The user indicates which factors to include in the analysis and assigns a *priority* to the factor criteria—

absolutely necessary, important, or desirable—which indicates an importance of attaining the criteria for a given factor. The system uses the factors to conduct constraint relaxation on the resulting search. The search yields sets of materials ranked by *acceptability rating*—superior, satisfactory, marginal, or unsatisfactory. The system further prunes the ranked list by eliminating similar members of the same rating class that differ only in features (with commensurate increased cost) that are not pertinent to the application. In this case, the system will select the least expensive material of a similar set.

The system then conducts a slightly broader search by relaxing the *desirable* and *important* priorities. This secondary search process will include materials which qualify on the margin, but usually at a much lower cost. This allows the user to examine cost-performance trade-offs.

The authors performed 19 different application tests with GERES and compared the system's results with those of 5 different material domain experts. In 11 of the cases, GERES' results were the same as the domain experts'. In cases where GERES' results differed, the system either included materials deemed unsuitable for the application or did not list suitable materials. GERES included unsuitable materials in its search results since the system did not include all pertinent performance factors (e.g., surface finish or the presence of snap-fits) and because the system did not support sufficiently fine discrimination of factor criteria levels. Omitted materials were the result of incorrect material stiffness estimates at elevated temperatures. The authors believe that these

shortcomings were correctable. However, GE Plastics does not use the GERES system today.

In summary, knowledge-based systems for material selection have proven to be proficient at identifying materials that satisfy certain performance criteria, and they are probably well-suited for training inexperienced designers. However, knowledge-based material selection systems suffer the following drawbacks:

- 1) They don't consider combinations of material properties and geometry.
- 2) They are usually limited to a narrow material domain.
- 3) They don't consider manufacturing cost.
- 4) They don't provide a good means for cost-performance tradeoffs.

2.4 Application-based Approaches

Prior designs can offer a wealth of information about materials and processes well-suited for a particular application. Of course, details about the design requirements, application material and cost, performance and processing weaknesses, and new functional requirements are necessary. A relatively recent example of a systematic approach using "templates" of prior applications using engineering thermoplastics is provided by Richards, et al. (1995). This approach allows the user to start with an existing *application profile* (or, start from scratch) to begin a material selection session. Examples of currently available application profiles are provided in Table 2.8.

Table 2.8: Application profiles from Richards (1995)

<i>Aircraft</i>	Interior
<i>Automotive</i>	Console
<i>Business Equipment</i>	Desktop computer enclosure Keyboard enclosure Portable computer enclosure Wearable computer enclosure
<i>Telecommunications</i>	Hand-held computer enclosure Portable phone
<i>Power Tools</i>	Power tool field case

An application profile contains the design specifications for the application. The design specifications include *necessary* and *desirable* material properties, *design dependent considerations*, and user-assigned *relative importance* of the application properties and processibility (including ease of flow, warpage, and dimensional stability). The necessary and desirable properties (Table 2.9) indicate properties (and corresponding values) that are absolutely necessary, or properties (and an indication whether a property should be minimized or maximized) that are important to the application. The design dependent considerations (Table 2.10) are design objectives that can be met with a combination of material property and geometry or application requirements that may affect system behavior. For instance, system flexural stiffness can be increased by increasing a cross-section thickness or by using a material with a higher flexural modulus. In addition, the nominal application operating temperature will have a direct bearing on the material stiffness, and hence, system flexural performance.

Table 2.9: Material properties considered by Richards (1995)

Property Class	Properties	Properties
<i>Mechanical</i>	Rockwell Hardness (L, M, and R) Taber Abrasion (CS-17, 1 kg) Fatigue Limit (2.5 MM cycles) K _{factor} vs steel ($\times E^{-10}$, PV=2000 psi-fpm) K _{factor} vs self ($\times E^{-10}$, PV=2000 psi-fpm)	DUL (4000psi; room & 158 °F) PV Limit (100 fpm) Coefficient of friction on self (static) Coefficient of friction on steel (static) Coefficient of friction on steel (kinetic)
<i>Impact</i>	Ductility ratio Impact energy @peak (73 °F) Impact energy @peak (-20 °F)	Impact energy @peak (-40 °F) Impact total energy (73 °F) Impact total energy (-20 °F)
<i>Thermal</i>	Vicat softening temperature (rate B) HDT (66/264 psi) Thermal conductivity CTE (flow) Specific heat	Thermal index (electrical properties) Thermal index (mech. prop. w/impact) Thermal index (mech. prop. w/o impact) Brittleness temperature Glass transition temperature
<i>Physical</i>	Specific gravity (solid/ color) Specific volume Density Water absorption (24 hours @73 °F)	Mold shrinkage (flow) Warpage index Poisson's ratio Halogen content
<i>Optical</i>	Light transmission Haze Refractive index Yellowness index	Gloss (untextured @60 °F) Gloss (textured @60 °F, MT-1055-2) Low gloss achievable Limited colors
<i>Electrical</i>	Volume resistivity Surface resistivity Dielectric strength in air (62/125 mils) Dielectric strength in oil (62/125 mils) Dielectric constant (50/60/100 Hz) Dielectric constant (1/100 kHz)	Dielectric constant (1 MHz) Dissipation factor (50/60/100 Hz) Dissipation factor(1/100 kHz) Dissipation factor(1/2450 MHz) Arc resistance (Tungsten GE)
<i>Flame Characteristics</i>	FAA Flammability (passes) OSU 2 min heat (release rate) OSU peak heat (release rate horizontal) Vertical burn (extinguish time) Vertical burn (drip time) Vertical burn (length) Oxygen index (LOI)	NBS smoke dens. (flaming D _s 4 min) NBS smoke dens. (flaming D _{max} 20 min) NBS smoke dens. (smolder D _{max} 20 min) Radiant panel flame spread index FMVSS 302 burn rate (0.10"nominal) FMVSS 302 burn rate (0.05"nominal)
<i>Other</i>	FDA approval UV resistance	Electroplatability
<i>Chemical Compatibility</i>	Hydrocarbons (aliphatic/aromatic) Halogenated hydrocarbons (fully/partly) Alcohols/ Phenols/ Ketones/ Amines Esters/ Ethers/ Alkalies Acids (inorganic/organic/oxidizing) Greases (non-reactive organic esters) Hot water (< 80 °C)	Oils (unsaturated aliphatic mixtures) Waxes (heavy oils) Petrol Cooling liquid (glycol) Brake fluid (heavy alcohol) Detergents/Cleaners

Table 2.10: Design dependent considerations from Richards (1995)

Design Dependent Considerations	Range
<i>Nominal Temperature</i>	[value] °F
<i>UL-94 Flammability Class</i>	none/HB/V-2/V-1/V-0/5V
<i>Limiting Factors</i>	
<i>Tensile Stiffness</i>	yes/no
<i>Flexural/Torsional Stiffness</i>	yes/no
<i>Tensile Strength</i>	yes/no
<i>Tensile Fatigue (@room temp.)</i>	yes/no
<i>Flexural/Torsional Fatigue (@room temp.)</i>	yes/no

Example run

As an example, consider a desktop computer housing. The application profile (a template provided by the material selection system) is given in Table 2.11. In this application, the relative importance of the application properties is weighted more heavily than processability (although it is not clear from any of the system documentation exactly what impact this has on the scoring mechanism). The nominal temperature (150 °F), flammability rating (5V), and heat distortion temperature ($HDT \geq 160$ °F) are typical for this class of components. The flexural stiffness and tensile strength requirement reflect the fact that the housing will support a monitor while in use. The impact, optical, and chemical compatibility properties desired are also typical of this class of components.

Table 2.11: Application profile (design requirements) for a desktop computer housing

Performance factor	Level
<i>Application</i>	Relative performance = 80.0
<i>Processibility</i>	
<i>Warp and dimensional control</i>	Relative performance = 2.0
<i>Ease of flow</i>	Relative performance = 8.0
Design dependent considerations	
<i>Nominal Temperature</i>	150 °F
<i>Flexural/torsional stiffness</i>	yes
<i>Tensile strength</i>	yes
<i>UL-94 flammability class</i>	5V
Necessary properties	
<i>HDT @264 psi</i>	≥ 160 °F
Desirable properties	
<i>Impact</i>	Relative performance = 4.0
<i>High ductility ratio</i>	Relative performance = 10.0
<i>Optical</i>	Relative performance = 10.0
<i>High low-gloss achievable</i>	Relative performance = 2.0
<i>Low limited colors</i>	Relative performance = 8.0
<i>Chemical compatibility</i>	Relative performance = 4.0
<i>High detergents, cleaners</i>	Relative performance = 10.0

Selection Results

Table 2.12 shows the materials selected by the system. The list of 5 materials include a PC/ABS alloy (Cycloy™), three PBT materials (Valox™), and a polycarbonate (Lexan™). The PC/ABS material is a typical material for computer housings. The PBT

and polycarbonate are significantly higher-performance materials but receive relatively high rankings due to their cost-performance trade-off.

Table 2.12: Desktop computer housing material selection results

Property	Cycloley C2000	Valox 357	Lexan 304	Valox 457	Valox 6000
Relative material cost	1.2	2.1	2.0	2.3	2.6
Relative mold cycle time	1.1	1.6	1.5	1.7	1.8
Relative part fabrication cost	2.2	3.7	3.5	4.0	4.4
Processability score	7.0	3.9	4.9	4.0	5.4
Application property score	4.0	4.7	3.5	3.8	3.9
Overall score	4.6	4.6	3.7	3.8	4.2
Relative value	2.05	1.22	1.08	0.96	0.95

Critique

In discussions with the author of this system (a noted expert in resin applications at GE Plastics), it became obvious that the selection procedure was tuned to give realistic results in the sample application profiles. And, there is plenty of opportunity for tuning since the selection system includes so many *relative performance* weights. One clear advantage of the material selection system developed by Richards (1995) is the breadth of material properties available for the analysis (limited to GE Plastics resins, of course).

The benefits of this application-based material selection system are as follows:

- 1) The past can be a very good guide to material selection. There are clear reasons why engineers choose a material for a particular application. In any design project that requires specifying a material, assessing similar applications and material choices is imperative.

- 2) The selection system can implicitly consider the combination of material properties and geometry that determine *system* performance. In the approach by Richards, design dependent considerations take into account material properties and geometry. The business equipment application profile assumes a nominal part thickness for a given material based on material properties and design requirements.
- 3) The selection system implicitly captures processability costs. The relative importance of ease-of-flow and dimensional control are provided for sample application profiles. These preference weightings are, in the system's author's opinion, typical of applications of that particular type. The processing requirements are *implicitly* represented in the resulting candidate materials.
- 4) Application-based methods are perhaps best at indicating the pertinent material properties that are not a strong function of geometry or processing. Examples of these material properties include colorability, pertinent material impact properties, optical requirements, chemical compatibility, etc.

The shortcomings of the application based approach are:

- 1) The approach is best when functional requirements change slowly. If a current application is experiencing impact failures, a designer can substitute a similar material with greater impact resistance. For an application with largely different application requirements, then the solution may not be as simple as switching among material grades. Effective application approaches require detailed history of the application requirements and analysis results that justify the past choice of a particular material.
- 2) The implicit nature of the material/geometry interaction. In the application-based approach outlined above, the user can indicate only the considerations important to the design—tensile strength, flexural stiffness, etc. It is not

explicitly clear what effects a particular nominal wall thickness and application temperature have on material and manufacturing cost.

- 3) The implicit nature of the processing cost. Likewise, application profiles indicate a *typical* balance of relative weight between meeting application and processing requirements. What is not *explicit* is the effect that a particular material or geometry has on manufacturing cost.
- 4) The application-based approach detailed above uses relative performance weights to rank materials. This technique obscures the true cost vs. performance tradeoffs that must be made in any material selection. Without a clear understanding of how *preferences* or *weights* map material properties to a single material preference scale, cost-performance tradeoffs are impossible.

2.5 Ashby Approach

Ashby has proposed a method for selecting a material from among all the conventional engineering materials (Ashby, 1992). In this approach, the author uses *performance indices* to rank material *classes* and *members* by their *design limiting performance properties*. Table 2.13 lists the material classes and members considered by Ashby.

Table 2.13: Material properties considered by Ashby

<i>Engineering Alloys</i>	Aluminum Alloys Copper Alloys Lead Alloys Magnesium Alloys Molybdenum Alloys Nickel Alloys	Steels Tin Alloys Titanium Alloys Tungsten Alloys Zinc Alloys
<i>Engineering Polymers</i>	Epoxies Melamines Polycarbonate Polyesters Polyethylene	Polyformaldehyde Polymethylmethacrylate Polypropylene Polytetrafluorethylene Polyvinylchloride
<i>Engineering Ceramics</i>	Alumina Diamond Sialons	Silicon Carbide Silicon Nitride Zirconia
<i>Engineering Composites</i>	Carbon Fiber Reinforced Polymers Glass Fiber Reinforced Polymers	Kevlar Fiber Reinforced Polymers
<i>Porous Ceramics</i>	Brick Cement Common Rocks	Concrete Porcelain Pottery
<i>Glasses</i>	Borosilicate Glass Soda Glass	Silica
<i>Woods</i>	Ash Balsa Fir	Oak Pine Wood Products
<i>Elastomers</i>	Natural Rubber Hard Butyl Rubber Polyurethanes	Silicon Rubber Soft Butyl Rubber
<i>Polymer Foams</i>	Cork Polyester	Polystyrene Polyurethane

Table 2.14 shows the material properties considered by Ashby. These properties are considered *design limiting*; i.e., they characterize the general limits of material performance, and Ashby uses these properties to examine relative performance between material classes.

Table 2.14: Design limiting material properties

General	Relative Cost	[]
	Density	Mg/m ³
Mechanical	Elastic Moduli	GPa
	Strength (yield/ultimate/fracture)	MPa
	Toughness	kJ/m ²
	Fracture Toughness	MPa m ^{1/2}
	Damping Capacity	[]
	Fatigue Ratio	[]
Thermal	Thermal Conductivity	W/m °K
	Thermal Diffusivity	m ² /s
	Specific Heat	J/kg °K
	Melting Point	°K
	Glass Temperature	°K
	Thermal Expansion Coefficient	°K ⁻¹
	Thermal Shock Resistance	°K
	Creep Resistance	[]
Wear	Archard Wear Constant	MPa ⁻¹
Corrosion/Oxidation	Corrosion Rate	[]
	Parabolic Rate Constant	m ² /s

Table 2.15 shows an example of the *performance indices* that Ashby employs to rank material classes on various property axes.

Table 2.15: Ashby performance indices for minimum weight, cost, or energy

Tie (tensile strut)	E/ρ	σ_f/ρ
Torsion bar or tube	$G^{1/2}/\rho$	$\sigma_f^{2/3}/\rho$
Beam	$E^{1/2}/\rho$	$\sigma_f^{2/3}/\rho$
Column (compression strut)	$E^{1/3}/\rho$	σ_f/ρ
Plate	$E^{1/3}/\rho$	$\sigma_f^{1/2}/\rho$

Example Run

An example will best illustrate the utility of the Ashby approach. Consider a computer housing which will contain computer hardware components, and on top of which will rest a computer monitor. For this example, we would like to minimize cost, and we can tolerate no more than 5 mm of deflection at the center of the housing. We can model the top of the computer housing as a flat plate and the computer monitor as a distributed load. Figure 2.4 shows the plate with prescribed geometry, boundary, and loading conditions.

Figure 2.4: Flat plate and prescribed conditions for the Ashby example

The equation for maximum deflection of a flat plate with fixed edges under a uniform load is

$$\delta_{\max} = \frac{\alpha P_0 b^4}{Eh^3} \quad (2.17)$$

where

$\delta_{\max}$ = maximum deflection

α = geometric constant

P_0 = uniform load

b = plate width

h = plate thickness

E = modulus of elasticity

The material cost of the flat plate can be expressed by

$$cost = abh\rho C \quad (2.18)$$

where

ρ = material density

C = material cost [$\$/kg^3$]

Solving for the free variable h in Equation 2.17 and substituting into Equation 2.18 yields

$$cost = ab \left(\frac{\alpha P_0 b^4}{E \delta_{\max}} \right)^{1/3} \rho C \quad (2.19)$$

Rewriting Equation 2.19 by isolating the functional, geometry, and material variables yields

$$cost = \left(\frac{P_0}{\delta_{\max}} \right)^{1/3} \cdot (\alpha a^3 b^7)^{1/3} \cdot \left(\frac{\rho C}{E^{1/3}} \right) \quad (2.20)$$

For the minimum cost material, we will want to minimize the last factor of Equation 2.20, or, considering the inverse, maximize M , where M is the merit index:

$$M = \frac{E^{1/3}}{\rho C} \quad (2.21)$$

Ashby provides material charts which show graphically the classes of materials which will maximize the merit index (Equation 2.21). Using the merit index in Figure 2.5, we can rank the classes of materials with the best performance. At this point, Ashby uses engineering experience to further prune the list by eliminating candidates with obvious performance flaws. We will do the same in this case.

Selection Results

Figure 2.5: Young's Modulus vs. relative cost per unit volume from Ashby

Table 2.16: Materials with the best stiffness-to-cost performance for the flat plate example

Porous Ceramics	23 - 120	0.1 - 2.2	2.0 - 3.8	Good in compression, but not in tension
Woods (to grain)	2 - 20	1.5 - 10	0.2 - 0.8	Interesting choice
Polymer Foams	0.01 - 0.15	0.05 - 0.9	0.1 - 0.4	Not strong enough
Wood Products	1.5 - 5.0	0.8 - 1.7	0.5 - 1.0	Interesting choice
Woods ($\perp$ to grain)	0.12 - 1.5	0.1 - 0.85	0.2 - 0.8	Interesting choice
Cast Irons	160 - 190	5.5 - 20.0	7.0 - 7.8	Stiffness to weight performance is not good
Mild Steels	190 - 250	30.0 - 220	7.5 - 8.3	Stiffness to weight performance is not good
Glasses	50 - 80	0.50 - 1.0	2.2 - 2.5	Good in compression, but not in tension
Eng. Polymers	0.2 - 12	0.45 - 7.0	0.85 - 2.3	Overall, many good qualities
Aluminum Alloys	60 - 82	12.0 - 50.0	2.7 - 2.9	Another interesting choice; pricey;
GFRP	20 - 50	15.0 - 65.0	1.3 - 2.0	Expensive stuff; Expensive to manufacture
Magnesium Alloys				Interesting choice, but expensive;

Of course, we have not included other design constraints, only that we want the housing to be stiff and inexpensive. Other constraints would also include durability (good impact resistance and strength), resistance to creep at moderate temperatures ($\approx 50^\circ\text{C}$), inexpensive to manufacture in quantities (say, 200,000 units per year), maximum thickness less than a prescribed amount (for package size constraints), lightweight, UL approval, etc. All of these will narrow down the choices still further.

Wood and various wood products are an interesting choice since they seem to satisfy the basic requirements that we have listed. However, one important issue that we haven't addressed is manufacturability, especially in large quantities. Wood products present a problem here.

Cast irons and mild steels are too heavy. Mild steels are often used in business equipment housings, but for our computer housing application we would either require heavy gauge sheet metal or use a thinner sheet metal but provide internal reinforcements to support the monitor.

Critique

In summary, the benefits of the Ashby approach are as follows:

- 1) The Ashby method provides a technique for ranking classes (and members) of materials in the set of all engineering materials.
- 2) This ranking method is based on physical principles and material properties.
- 3) The physical principles apply to simplified geometries and loading conditions, which are appropriate for the stage of design at which this method is targeted.
- 4) Provides a method for handling multiple design objectives.
- 5) This method is especially useful for the design of novel products, for which there may be no previous examples. It is also useful for material selection rationalization for older designs, and may also be useful when conducting material variety reduction in a product design.

Several enhancements or extensions to the Ashby method include:

- 1) A more systematic method for reducing the initial list of ranked materials. Currently, Ashby uses engineering experience to further prune the list; while requiring engineering experience is not necessarily an unusual requirement, a systematic method of doing this is desirable.

- 2) A systematic approach to more detailed material selection. Ashby's method will generate a ranked list of material classes or members. A method of narrowing the search even further is desirable.

2.6 System Performance-based Approach

The fundamental challenge in material selection is reducing the number of candidate materials available to a manageable set, suitable for detailed analysis. Ideally, this reduction to a limited set of suitable materials will incorporate the costs induced by choice of geometry or processing constraints without eliminating potentially optimum materials. Most existing material selection approaches seek to do this by pruning materials based on properties that clearly eliminate some materials and ranking the remaining materials based on a scoring mechanism. These scoring mechanisms attempt to capture desired designer's preferences through property or behavior weighting and incorporate these weights into a composite material score. The attractiveness of this approach is that it allows designers to quickly arrive at a set of candidate materials without performing any detailed analysis. The primary drawback to such an approach is that preference schemes don't provide an intuitive mapping between desired material properties or design requirements and resulting material scores. For instance, what does indicating that meeting application requirements are weighted twice as much as processability concerns mean?

This dissertation proposes an alternative material preference scheme. However, this scoring scheme is based on mechanical and manufacturing performance models that map

design requirements directly to manufactured part cost. The advantage of such an approach is that it allows the user to examine the tradeoffs between application requirements and resulting material ranking. Moreover, the relationship between design requirements and material ranking has intuitive meaning; the user can develop a clearer mental model of how performance requirements impact material selection.

Of course, material selection is not simply a matter of mapping materials, via design requirements, to a comparative scale. The exercise requires a more systematic approach that incorporates geometry and process choice. The following is a high-level outline of material selection that incorporates the method of Ashby (detailed above) and performance-based material selection, the subject of this dissertation (Figure 2.6).

- 1) First, determine your highest priority design goal and a rough geometry, and use Ashby's method to rank materials according to that merit index. Such design goals may be high stiffness with low cost, or high fracture toughness with low density. At this point you will have several viable material candidates (material classes and/or members such as engineering polymers, mild steels, aluminum alloys, etc.).
- 2) Use secondary design goals or constraints to further prune the list. This can be done via Ashby by ranking materials using the secondary design goals to generate a reduced set of material classes and members.
- 3) Now use a system performance-based method to narrow the search even further. This is the subject of this dissertation. It applies to engineering thermoplastic resins manufactured by injection molding.

- 4) Use detailed engineering analysis to make the final decision. This will include structural and process simulation, and require detailed material characterization.
- 5) Prototype and test product to make the final decision when necessary.

Figure 2.6: An approach to systematic material selection

CHAPTER 3

THERMOPLASTIC MATERIAL TAXONOMY AND BEHAVIOR

3.1 Introduction

This dissertation focuses on thermoplastics suitable for structural applications and for components manufactured by the injection molding process. Thermoplastics suitable for structural applications is not a precise definition, but in general this requirement presumes a modulus greater than 1,000 MPa (145,000 psi). This chapter explains the material taxonomy, general material property ranges for the polymer families under consideration, and material tests and behavior relevant to system cost-based material selection.

3.2 Material Taxonomy

Materials can be classified in a number of ways—polymer manufacture, chemical class, microstructural properties, and temperature. Demaid, et al. (1996) provide a detailed description of polymer classification schemes and their respective merits. Polymer classification schemes provide a means of generalizing about materials at a high level—nylons are sensitive to moisture, polycarbonates are susceptible to stress cracking, PVC's are inherently UV stable, etc. This dissertation uses a chemical family taxonomy (Figure 3.1) which enjoys the benefit of an established nomenclature and conveys

meaning beyond just the chemical structure. Table 3.1 summarizes the general behavior and cost range for selected polymer classes.

Figure 3.1: Material Taxonomy for system cost-based material selection

Table 3.1: Selected general polymer class property ranges and cost

ABS	1654-2930	78-121	138-343	2.82-4.98
ABS-Filled	4130-14478	88-104	58-88	7.94-7.94
ABS/PBT	1930-11710	90-185	37-69	4.19-5.18
ABS/PBT-Filled	5510-9990	200-205	80-90	4.30-5.29
ABS/PC	1930-3000	100-120	320-673	4.98-5.58
ABS/PC-Filled	4130-7350	99-131	74-213	5.95-7.00
ASA	1378-2068	71-97	110-379	3.62-3.62
HDPE	920-1720	49-66	12-80	3.24-5.89
HDPE-Filled	3930-8610	110-121	58-299	3.09-6.35
PA 66	1310-8750	65-249	4-245	4.74-5.82
PA 66-Filled	7230-11780	105-252	80-128	3.00-8.00
PBT	1520-8273	54-215	25-961	4.54-6.81
PBT-Filled	3100-8549	188-210	58-96	4.85-7.10
PC	1929-9652	65-165	640-907	5.45-5.86
PC-Filled	5170-15670	141-149	88-138	7.19-7.87
POM	827-2960	82-148	42-74	4.03-4.03
POM-Filled	2580-7579	118-163	37-42	4.54-4.54
PP	1170-10342	54-99	21-267	1.06-5.89
PP-Filled	1310-9490	57-160	24-336	2.40-2.65
PPE/PS	2410-2420	80-127	181-213	5.67-5.67
PPE/PS-Filled	7920-13850	132-260	42-80	5.05-8.00
PS	1792-3170	77-93	14-170	2.17-5.40
PS-Filled	6550-6610	93-123	26-69	2.98-3.37
PVC	2190-2860	65-96	53.4-1335	1.37-2.58
PVC-Filled	3792-7584	77-83	90-90	2.40-4.00

3.3 General Properties and Attributes

3.3.1 Density

Density is the mass per unit volume at a particular temperature. The density of polymers exhibits a strong sensitivity to temperature and pressure, so density is not a single data point (see Section 3.6.2). However, for closed-form cooling calculations, this

dissertation uses the single data point density at standard temperature and pressure (outlined in ASTM D972).

3.3.2 Cost

Cost is perhaps the most difficult material information to acquire. Material suppliers don't usually publish cost information, and even if it can be acquired, this information changes over time. Some researchers overcome this problem by normalizing the cost of the materials by some reference material (Ashby, 1992). For uniform relative increases, this approach is adequate. This technique does not account for changes in material production quantities or world-wide shortages in the production of certain polymers. For example, bulk prices for polycarbonate doubled in the Far East during 1995 and increased 40% in Europe during the same period (Mapelston, 1996) due to production under-capacity and strong demand.

In this dissertation, polymer cost data used is the latest available from material suppliers. The specific price used in cost calculations is for natural color at truckload quantities (> 40,000 lbs).

3.4 Mechanical Behavior

3.4.1 Stiffness and Strength

Figure 3.2 shows tensile stress-strain curves for generic filled and unfilled thermoplastics. In general, the yield strength, σ_y , for a material is the stress level which

will cause a specified amount of permanent deformation (usually 2% strain) after removal of the stress. However, plastics exhibit viscoelastic behavior; after removal of the stress load, the plastic may continue to recover over time. For this reason yield points for plastics are often indicated as stress ranges, or σ_y is estimated.

Figure 3.2: General tensile stress-strain curve for a filled and unfilled thermoplastic

This dissertation uses flexural modulus and yield for performance calculations. Three- or four-point bending tests determine flexural modulus (Figure 3.3), and various standards govern the specimen preparation and testing conditions. Theoretically, tensile strength and modulus are equivalent to flexural modulus and strength. The theory assumes pure bending, and isotropic and homogeneous material properties (Brown, 1988). In practice, the flexural modulus of a material is an approximation of its tensile modulus. However, often materials are not loaded in pure tension but in tension and

compression; this dissertation uses flexural modulus and flexural yield in part performance models for this reason.

Figure 3.3: 3-point bend test (left) and 4-point bend test (right) for flexural modulus

3.4.2 Time, Temperature, and Stress Dependence

Plastic materials also display significantly varied behavior under the influence of time, temperature, and applied stress level. For this reason, a material selection methodology must discriminate on at least a temperature basis at the pruning level, and in addition consider time (creep) and stress level during detailed material selection. The *deflection temperature under load* (DTUL; also known as heat distortion temperature, HDT) provides a means of comparing and pruning materials. The DTUL is the temperature at which a polymer achieves a certain flexural modulus (as dictated by ASTM D648 and ISO 75). Figure 3.4 shows the testing apparatus for measuring DTUL. Figure 3.5 shows DTUL ranges as a function of cost for several thermoplastics.

Figure 3.4: Deflection temperature under load (DTUL) testing apparatus (Malloy, 1994)

Figure 3.5: Deflection under load temperature as a function of cost

The heat distortion temperature is a single temperature at which an arbitrary plastic beam deflects a certain amount under a certain load. For this reason, it is not suitable for any design analysis. Plastics exhibit a marked decrease in stiffness over long periods of time, and especially at elevated temperatures and stresses. Creep tests yielding strain vs. time curves conducted at various temperature and stress levels provide a useful means of comparing materials at the detailed selection level. Figure 3.6 shows strain versus time for a filled PC and an unfilled ABS.

Figure 3.6: Strain versus time for a filled PC and unfilled ABS polymer

On a detailed material selection level the creep data is actually used in mechanical performance calculations to perform material selection. Time- and temperature-dependent data for engineering thermoplastics are a much better means than HDT of capturing

temperature dependent material effects, since temperature dependent stiffness is not a single data point.

3.4.3 Impact Behavior

Impact strength measures the ability of a polymer to withstand high-rate, impulse loading. The Izod impact test (Figure 3.7) employs a swinging pendulum to impart an impact force on a plastic specimen (ASTM D256). However, this test is only an indication of relative performance between polymers (Trantina, 1994) since the units of impact strength (energy per unit length) are not useful for engineering calculations. In addition, impact performance is very much a function of specimen geometry, loading rate, and temperature. Therefore, impact strength serves only to rank materials.

Figure 3.7: Izod test configuration (Trantina, et al., 1994)

3.4.4 Fatigue Behavior

Fatigue data is often provided in the form of stress vs. cycles to failure (S-N curves; Figure 3.8). S-N curves are generated at certain loading frequencies and environmental temperatures, but fatigue behavior of plastics is also a strong function of loading

waveform, forcing function control (load or displacement control), load level, type of load. SN data is therefore limited to a first-order estimation of life prediction.

Figure 3.8: Applied stress vs. cycles to failure for an ABS and PC

3.5 Thermal Properties

3.5.1 Thermal Conductivity

This dissertation uses thermal conductivity for cooling time calculations. Thermal conductivity is a measure of the rate at which heat is conducted through a solid at steady state. Figure 3.9 shows the typical apparatus for measuring thermal conductivity, although this is not the only means, depending upon the phase of the polymer at the test temperature (see ASTM C177).

Figure 3.9: Thermal conductivity is the rate heat is conducted through a solid (Ashby, 1992)

Thermal conductivity data is given as a function of temperature or as a single data point. In the closed form equations in this dissertation, we use the single data point thermal conductivity, which we take as the average thermal conductivity over the tested temperature range (Figure 3.10).

Figure 3.10: Thermal conductivity as a function of temperature

3.5.2 Specific Heat

Specific heat is the measure of the energy required to raise the temperature of a unit mass of a material one degree (ASTM C351 provides testing details). This dissertation uses specific heat in the cooling time calculations. Figure 3.11 shows specific heat as a function of temperature (at constant pressure) for an amorphous (PC) and semi-crystalline (PBT) thermoplastic. The sharp spike in the specific heat for the semi-crystalline material reflects the increase in energy required for melting the polymer. This dissertation uses the average specific heat over the tested temperature range.

Figure 3.11: Specific heat as a function of temperature

3.6 Dimensional Properties

3.6.1 Mold Shrinkage

Molding thermoplastic parts that meet dimensional tolerances in a cost-effective manner poses several challenges to the designer. The designer must understand the reasonable tolerance limits for candidate materials, molders, and particular molding process control. Typically, designer's or molders will use material *mold shrinkage* data to estimate achievable part tolerances (Malloy, 1994).

However, part shrinkage is a system behavior—a function of process conditions, orientation, geometry, and material properties. Therefore, mold shrinkage data is of limited use when it comes to part design. A more complete picture of the material response to processing conditions is needed, and material PVT behavior fills that role.

3.6.2 PVT Behavior

Figures 3.12 and 3.13 show PVT relationships for an amorphous and a semi-crystalline polymer. Semi-crystalline polymer densities exhibit a greater sensitivity to temperature and pressure than do amorphous polymers and, in general, are less desirable for tight-tolerance conditions. Also, the density of the molten polymer is generally more sensitive to variations in temperature and pressure than the polymer in its solid phase.

Figure 3.12: PVT diagram for an amorphous polymer

Figure 3.13: PVT diagram for a semi-crystalline polymer

For purposes of numerical analysis, the PVT relationship for a polymer is often expressed as a two-dimensional curve fit in pressure and temperature. Several functional forms of PVT behavior for a polymer exist, and a more common one used by many injection molding process simulation codes is the Double-domain Modified Tait equation (Zoller, 1989), given below:

$$v(T, p) = v_0(T) \left\{ 1 + C \ln \left(1 + \frac{p}{B(T)} \right) \right\} + v_i(T, p) \quad (3.1)$$

where

$$\left. \begin{aligned} v_0(T) &= b_{1m} + b_{2m} \bar{T} \\ B(T) &= b_{3m} e^{-b_{4m} T} \\ v_i(T, p) &= 0 \end{aligned} \right\} \text{ for } T > T_i, \quad (3.2)$$

$$\left. \begin{aligned} v_0(T) &= b_{1v} + b_{2v} \bar{T} \\ B(T) &= b_{3v} e^{-b_{4v} T} \\ v_i(T, p) &= b_7 e^{(b_8 T - b_9 p)} \end{aligned} \right\} \text{ for } T < T_i \quad (3.3)$$

and

$$\begin{aligned} p &= \text{pressure} \\ T &= \text{temperature} \\ T_i &= b_5 + b_6 p = \text{transition temperature} \\ \bar{T} &= T - b_5 \\ C &= 0.0894 \text{ (universal constant)} \end{aligned} \quad (3.4)$$

In Equations 3.1 to 3.3, b_1 through b_6 are curve-fit constants determined from PVT data for a specific material. The PVT data or the fitted constants are available from material suppliers and are often supplied with simulation codes.

3.7 Other Issues

3.7.1 Flammability Ratings

The UL94 test is the commonly accepted material flammability classification. The class ratings are V-0, V-1, V-2, HB, and 5V is a secondary test/rating (V-0 is best; HB is worst). The 5V rating is added to the first rating if the material passes the second test. The test essentially characterizes whether the material continues to burn after a flame is removed. The rating is dependent upon specimen thickness. A particular material may have different ratings for different thicknesses, but in general a material will only have one or two thickness/rating combination listed. The flammability rating limits minimum wall thicknesses in some cases. In this sense resistance to flammability is a system property.

3.7.2 Chemical Compatibility

Plastic materials exhibit a broad range of resistance to attack from chemicals. In many cases polymers enjoy an advantage over many engineering materials in their ability to withstand harsh chemical environments. In general, the semi-crystalline materials are less susceptible to chemical degradation than amorphous materials. However, resistance to

chemical degradation is affected to some degree by applied stress level, temperature, and the presence of other chemical agents and radiation sources. Several sources list the qualitative resistance of plastics to chemical exposure (Dominghaus, 1988; Ashby, 1994; see Table 3.2). From a materials selection perspective, resistance to degradation by a particular chemical alone can determine the suitability of a plastic for an application. In this sense, chemical compatibility is a material property as opposed to a system property.

Table 3.2: Resistance of selected polymer families to specific chemicals (Dominghaus, 1988[§])

Chemical	PE	PP	PVC	PS	PC	PMMA	PA6	PA66	PBT	PET	PBI	PI	PFA	PTFE
Hot water	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Cold water	+	•	+	+	+	+	+	•	•	-	-	+	•	-
Weak acids	+	+	+	+	+	•	•	-	+	+	•	+	+	+
Strong acids	•	+	•	•	•	-	-	-	•	•	-	+	+	+
Oxidizing acids	-	•	-	-	-	-	-	-	•	•	•		+	+
Hydrofluoric acid	•	•	•	•	•	•	-	-	•	+	+		-	•
Strong alkalis	+	+	+	+	+	+	+	+	-	•	+	+	+	-
Weak alkalis	+	+	+	+	+	•	+	•	-	-	+	+	+	+
Inorganic salts	+	+	+	+	+	+	+	+	•	+	+	+	+	+
Halogens	•	•	-	•	-	•	-	-	+					+
Aliphatic hydrocarbons	+	+	-	+	+	+	+	+	+	+	+		+	+
Chlorinated hydrocarbons	-	-	-	-	-	-	+	•	-	•	•		-	+
Alcohols	+	+	+	+	+	-	+	+	•	+	+		+	+
Esters		-	-	-	-	-	-	+	•	+	•		-	+
Ketones	•	-	-	-	-	-	•	+	•	+	-		-	+
Ethers	-	-	-	-	-	•	+	+	-	+	+		-	+
Aldehydes	+	-	-	-	-	+	•	•	-					
Amines	+	•	+	+	+	+	•	+	-					
Organic acids	•	•	•	•	+	-	+	•		+	•	+		+
Aromatic hydrocarbons	•	-	-	•	-	•	•	+	-	+	•		-	+
Fuels	•	-	-	-	+	-	+	+	•	+	+		-	+
Mineral oils	+	+	•	+	+	+	+	+	+	+	+		+	+
Greases, oils	+	+	+	+	+	+	+	-	+	+	+		+	+
Unsat. chlorinated hydrocarbons	-	-	-	-	-	-	+	•	-	•	•	•		
Turpentine	-	-	-	-	-	+	•	•	+	•	•			+

[§]Legend: +: resistant; •: limited resistance; -: not resistant;

CHAPTER 4

SYSTEM PERFORMANCE AND PROCESS MODELING

4.1 Introduction

System cost-based material selection uses simplified models of mechanical performance. This chapter first reviews the mechanical performance models—stiffness and strength—which, combined with material properties and part geometry, estimate part performance. Then, this chapter details the process models that impact part cost—cooling time, flow length, and system shrinkage.

4.2 Mechanical Performance Models

4.2.1 Strength

In most components it is desirable to avoid material yielding. For thermoplastics, the yield stress σ_y is a function of strain rate and temperature (Trantina, et al., 1994; see Figure 4.1):

$$\sigma_y = B_1 + B_2 \ln \dot{\epsilon} \quad (4.1)$$

where

B_1, B_2 = temperature dependent parameters for a particular material

$\dot{\epsilon}$ = strain rate

For room temperature or constant loading conditions, this dissertation uses the nominal material yield strength.

Figure 4.1: Stress vs. strain for polycarbonate (GF10%) at various temperatures and strain rates

4.2.2 Stiffness

Isotropic Plates

In many cases, structural geometry can be approximately modeled by a flat plate with prescribed loadings and boundary conditions. Using classical plate theory, many solutions exist for distributed and point loadings with free, simple and clamped edge

conditions (Timoshenko et al., 1959; Reismann, 1988; Young, 1989). Classical plate theory makes the following assumptions (Young, 1989):

- The plate is flat and of uniform thickness and material.
- The plate thickness is less than one-quarter the length of the shortest side.
- The maximum deflection is not more than about one-half the plate thickness.
- All forces are normal to the plane of the plate.
- All stresses are within the elastic limit.

As an example, consider a flat plate with clamped edges under a uniformly distributed load p_0 with length a and width b (Figure 4.2). The maximum deflection, δ_{max} , and maximum stress, σ_{max} , is given by (Young, 1989):

$$\delta_{max} = \delta\left(\frac{a}{2}, \frac{b}{2}\right) = \frac{\alpha P_0 b^4}{Eh^3} \quad (4.2)$$

$$\sigma_{max} = \sigma\left(\frac{a}{2}, \pm \frac{b}{2}\right) = \frac{-\beta_1 P_0 b^2}{h^2} \quad (4.3)$$

where

P_0 = uniform load

α = constant determined by a/b in Table 4.1

β_1 = constant determined by a/b in Table 4.1

h = plate thickness

E = modulus of elasticity

ν = Poisson's ratio = 0.3

Table 4.1: Constants α and β_1 for various values of a/b (Young, 1989)

α	0.0138	0.0188	0.0226	0.0251	0.0267	0.0277	0.0284
β_1	0.3078	0.3834	0.4356	0.4680	0.4872	0.4974	0.5000

Using allowable displacement as a functional constraint, the plate equations (together with material properties) will yield a plate thickness and maximum stress. Figure 4.3 shows required plate thickness as a function of allowable deflection for two thermoplastics. Plate thickness will have a direct impact on part cost—material volume used to achieve the function, a direct bearing on the part cooling time, and a restriction on achievable flow length.

Figure 4.2: Uniform Loading of a Flat Plate with Clamped Edges

Figure 4.3: Part thickness vs. allowable deflection for an ABS and PC

Isotropic Ribbed Plates

Ribbed structures are often used to stiffen parts at a lower overall material cost. There are several methods mentioned in the literature to account for ribbed reinforcements on flat plates (Minimum Total Potential Energy method, Sherman, et al., 1989; Equivalent stiffness method, Lifshay, 1980; Krishnamachari, 1993). The equivalent stiffness method finds 1) the deflection of a ribbed plate by using the deflection of a flat (unribbed) plate with an equivalent moment of inertia and 2) the maximum bending stress of the ribbed plate by using a flat plate with equivalent section modulus. An example will better illustrate this procedure. Consider the ribbed plate geometry in Figure 4.4. The neutral axis $\bar{Y}_{RP}$ of the ribbed plate is given by:

$$\bar{Y}_{RP} = \frac{A_P \bar{y}_P + N_R A_R \bar{y}_R}{A_P + N_R A_R} \quad (4.4)$$

where

$$A_P = \text{plate section area} = ah_p$$

$$\bar{y}_P = \text{distance to flat plate centroid} = \frac{h_p}{2}$$

$$A_R = \text{rib section area} = h_R (w_R - h_R \tan \alpha)$$

$$\bar{y}_R = \text{distance to rib centroid} = h_p + h_R - \frac{h_R}{3} \left[\frac{3w_R - 2h_R \tan \alpha}{2w_R - 2h_R \tan \alpha} \right]$$

$$N_R = \text{number of ribs}$$

$$h_p = \text{thickness of the ribbed plate}$$

The neutral axis $\bar{Y}_{FP}$ of the flat plate is given by:

$$\bar{Y}_{FP} = \frac{h}{2} \quad (4.5)$$

where

h = thickness of the flat plate

Figure 4.4: Ribbed plate and flat plate geometry

The moment of inertia I_{RP} of the ribbed plate section about its centroid of area x' is:

$$\begin{aligned}
 I_{RP} &\equiv \bar{I}_{x'} = (I_{x'})_p + N_R (I_{x'})_R \\
 &= \frac{N_R h_R^3}{12} \left[w_R - h_R \tan \alpha - \frac{h_R^2 \tan^2 \alpha}{3(w_R - h_R \tan \alpha)} \right] \\
 &\quad + \frac{ah_p^3}{12} + A_p \left(\bar{Y}_{RP} - \frac{h_p}{2} \right)^2 + N_R A_R \left(\frac{h_R}{3} \left[\frac{3w_R - 2h_R \tan \alpha}{2w_R - 2h_R \tan \alpha} \right] - \bar{Y}_{RP} \right)^2 \quad (4.6)
 \end{aligned}$$

where

$(I_{x'})_p$ = moment of inertia of the flat plate portion about x'

$(I_{x'})_R$ = moment of inertia of the rib portion about x'

The moment of inertia I_{FP} of the flat plate section about its centroid of area x' is:

$$I_{FP} \equiv \bar{I}_{x'} = \frac{ah^3}{12} \quad (4.7)$$

The section modulus is the ratio of the moment of inertia to the distance between the neutral axis (at x') and the point the farthest away from the neutral axis. For the ribbed plate, the section modulus S_{RP} is:

$$S_{RP} = \frac{I_{RP}}{h + h_R - \bar{Y}} \quad (4.8)$$

and for the flat plate, the section modulus S_{FP} is:

$$S_{FP} = \frac{I_{FP}}{\frac{1}{2}h} = \frac{ah^2}{6} \quad (4.9)$$

Then, to determine the required plate thickness h_p of a ribbed rectangular plate with an arbitrary isotropic rib pattern (same number of identical ribs per unit length on each side) using the flat plate equations (e.g., Equation 4.2), do the following:

- 1) Calculate the flat plate thickness h to satisfy the loading and environmental conditions, using Equation 4.2.
- 2) Calculate the moment of inertia I_{FP} of the flat plate section using Equation 4.7.
- 3) Now set the moment of inertia I_{RP} of the ribbed plate equal to I_{FP} and solve for the ribbed plate thickness h_p using Equation 4.6.

The maximum stress can be found in the same manner, using instead equivalent section moduli (Equations 4.8 and 4.9 above). The issue of shape and material selection is covered by Ashby (1992). He introduces non-dimensional shape factors to show that mechanical efficiency can be gained by combining material with shape. In fact, the particular cross-section of the plate geometry (flat plate vs. ribbed plate) will induce a unique ordering of materials in a sufficiently populated database.

To see this, consider the performance function for minimizing cost of a stiff computer housing (Equation 2.4):

$$cost = \left(\frac{P_0}{\delta_{max}} \right)^{1/3} \cdot (\alpha a^3 b^7)^{1/3} \cdot \left(\frac{\rho C}{E^{1/3}} \right) \quad (4.10)$$

To minimize cost, we would like to maximize the inverse of the last term (the merit index) of Equation 4. 10:

$$M = \frac{E^{1/3} \phi_R^c}{\rho C} \quad (4.11)$$

This is the same equation as the merit index of Equation 2.5, except that Equation 4.11 now contains the shape factor ϕ_R^c . For flat plates with the same shape, ϕ_R^c is constant and we can ignore it. But if we want to compare two plates of different shape, then we must consider the performance index of Equation 4.11.

Orthotropic Stiffness

For fiber-filled materials, fiber orientation after part filling will play a role in overall system stiffness. For simple geometries with an assumed gating configuration, using a cross-flow modulus as a certain percentage of in-flow modulus is suitable. This does require a more general form of the appropriate plate equations.

Time and Temperature Dependent Stiffness

In nearly all structural applications with engineering thermoplastics, designers must consider the effects of time, temperature, and stress level. Many studies have examined the behavior of test specimens under various loading conditions over time, and large volumes of data are available in the form of time-strain plots at various temperatures (Trantina, et al., 1994). For computational purposes, a second-order polynomial function in log time has exhibited reasonable correlation (Trantina, et al., 1994):

$$\varepsilon_t = A(\log t)^2 + B \log t + C \quad (4.7)$$

where

$$\begin{aligned} \varepsilon_t &= \text{creep strain (\%)} \\ t &= \text{time (seconds)} \\ A, B, C &= \text{material constants} \end{aligned}$$

To capture the effects of temperature, interpolation and extrapolation in natural log strain–inverse temperature space is adequate (Trantina, et al., 1994); i.e., solve

$$\ln \varepsilon_t = \frac{C_1}{T} + C_2 \quad (4.8)$$

for C_1 and C_2 at two nearby temperatures in conjunction with creep strains determined with Equation 4.7, and use Equation 4.8 to solve for the unknown creep strain at the new temperature.

In Equation 4.8:

$$\begin{aligned} \varepsilon_t &= \text{creep strain (\%)} \\ T &= \text{absolute temperature (}^\circ\text{)} \end{aligned}$$

For including time and temperature effects in a constant stress application, designers can use an *effective modulus* in the standard plate equations (e.g., Equation 4.2). The effective modulus E_{eff} is defined as:

$$E_{eff} = \frac{\sigma_0}{\varepsilon_t(t, T)} \quad (4.9)$$

where

σ_0 = constant initial stress

ε_t = creep strain

Figure 4.5 shows effective modulus as a function of application temperature for an ABS and PC at selected constant stress levels and at 100 hours (extrapolated). By using the time and temperature dependent effective modulus (E_{eff}) in the plate equations (Equation 4.2) we see the effect of temperature on meeting the prescribed stiffness requirements (Figure 4.6). Materials with temperature sensitive moduli are easily distinguished from the materials that retain stiffness at elevated temperatures.

Figure 4.5: Effective modulus as a function of temperature

Figure 4.6: Required part thickness as a function of temperature for selected thermoplastics

4.2.3 Impact

In many applications, dynamic impact loading of a part may induce failure. Plastics are often chosen for their ability to absorb high amounts of energy before permanent deformation. However, proper material and geometry selection is required to minimize the chance of failure under impact loading. Consider, for example, a ribbed plate subjected to a known impact load P (Figure 4.7). Woods, et al. (1995) have shown that the ratio of maximum principal stress, σ_1 , to yield stress, σ_y , as a function of strain rate is useful for ensuring *ductile* failure, which is a more desirable mode of failure than catastrophic *brittle* failure. They relate this stress ratio to plate thickness and rib fillet

radius (Figure 4.8). By ensuring that the rib radius to plate thickness ratio falls to the right of the region of brittle failure, defined by the line of constant σ_1/σ_y , the part will fail in a ductile manner. However, in some situations prescribing a larger fillet radius will induce *sink mark* in the region under the rib (indicated in the region labeled “processing problems” in Figure 4.8). In such a case, the designer will have to change the geometry or rely on more costly processing conditions to mold satisfactory parts.

Figure 4.7: Flat plate with rib under impact load P

Figure 4.8: Maximum principal stress to yield stress as a function of fillet radius r and plate thickness h

4.2.4 Fatigue

Fatigue is an additional mechanical constraint for a variety of plastic parts that are exposed to cyclic loading during their useful life. A designer can use S-N (Stress vs. Number of Cycles to Failure) curves from sample geometries to estimate the component life for a given design (Wyzgoski, 1995). In this case, using a functional constraint of desired number of cycles before failure will yield a lower limit on plate thickness to meet the required stress level.

4.3 Processing Cost Drivers

4.3.1 Cycle Time

Cycle time is the time required to mold one part (in a single cavity mold) and consists of mold closing time, injection time, cooling time, mold opening time, and part ejection time. In general, the cooling time is the largest component of cycle time. While process simulation can provide good estimates of required cooling time, there are approximate methods available for rough geometry. Equation 4.10 gives the estimated cooling time for a flat plate as shown in Figure 4.9 (Malloy, 1994). In this case, the wall thickness h has a large effect on cooling time; required cooling time directly links the geometry required to meet the specified functional performance to a manufacturing cost. Figure 4.10 shows cooling time as a function of nominal wall thickness for selected thermoplastics, using Equation 4.10.

Figure 4.9: Flat plate geometry for cooling calculations

$$t_{cycle} = \frac{h^2}{\alpha\pi^2} \ln \left[\frac{4}{\pi} \left(\frac{T_m - T_w}{T_e - T_w} \right) \right] \quad (4.10)$$

where

t_{cycle} = time for centerline to reach T_e (s)

h = plate thickness (m)

$\alpha = k/\rho c$: thermal diffusivity (m^2/s)

k = thermal conductivity ($\text{W}/\text{m}^\circ\text{K}$)

c = specific heat ($\text{J}/\text{kg}^\circ\text{K}$)

ρ = density (kg/m^3)

T_m = melt temperature ($^\circ$)

T_w = mold temperature ($^\circ$)

T_e = ejection temperature ($^\circ$)

Figure 4.10: Cooling time as a function of wall thickness for selected thermoplastics

4.3.2 Achievable Flow Length

Process simulation is often used to determine gating requirements to adequately fill a part. However, there are simpler models that permit an estimation of achievable flow length based on the radial filling of a center-gated disk (Kazmer, 1990). Figure 4.11 shows achievable flow length as a function of nominal wall thickness using curve fits from moldfilling calculations for selected materials using midpoint material processing set-points (melt temperature, mold temperature, injection pressure).

Achievable flow length can be mapped to cost in a number of ways. First, polymers with shorter flow lengths may require higher-capacity machines or require operating closer to the process window boundaries, resulting in a more difficult part to mold. Or,

for the same geometries, some materials may require a more complex gating scheme, and hence, higher tooling costs to manufacture the same part. This dissertation uses achievable flow length as a lower constraint on wall thickness. If the designer wishes to use a single gate and the standard recommended processing conditions, the achievable flow length for a particular thermoplastic will place a lower limit on wall thickness.

Figure 4.11: Achievable flow length as a function of wall thickness

4.3.3 System Shrinkage Behavior

While mold shrinkage data does provide a qualitative comparison of material dimensional stability, it does not explicitly capture the effects of process variables (packing pressure, mold and melt temperature). At advanced stages of design, injection

molding process simulation can estimate part shrinkage and out of plane distortion. However, results from this level of analysis usually come later in the design process, at which time it is more difficult to make the changes that simulation may suggest. This research employs a material shrinkage model that is explicitly based on process variables and suitable for candidate design selection. Plastic materials exhibit pronounced shrinkage behavior over the temperature and pressure ranges typically experienced in the injection molding process. While interactions with mold geometry and complex boundary conditions can make shrinkage modeling very complex, there exist simplified ways to estimate uniform part shrinkage based on known processing conditions and material properties (Bushko, 1995). This section explains 1) the use of polymer Pressure-Volume-Temperature (PVT) data to estimate part shrinkage and 2) the results and limitations of the PVT model.

The PVT Method

The PVT method for estimating shrinkage of an injection molded part uses the PVT relationship exhibited by the polymer and the approximate molding process conditions to estimate volumetric shrinkage, S_v , and linear shrinkage, S_L (Bushko, et al., 1995). Figure 4.12 shows a PVT diagram with two constant pressure curves (P_0 and P_{pack}), and an idealized process trace. The polymer enters the mold at point A in the molten state, and fills the mold at constant temperature under increasing injection pressure from P_0 to P_{pack} . At B, the polymer begins to cool at constant packing pressure P_{pack} . At C, the gate freezes off and the packing pressure can no longer be maintained. The polymer continues

to cool, only now at constant specific volume v_D , as the cavity pressure slowly decays. At D, the polymer has reached atmospheric pressure, and continues to cool to point E, but now at constant atmospheric pressure P_0 .

Figure 4.12: PVT diagram with molding process trace

The shrinkage is calculated using the specific volumes at the time at which the gate freezes (at point C, when no more polymer can enter the mold cavity) and the final part temperature (T_{room}) at point E. Volumetric shrinkage is then defined as

$$S_v = \frac{v_D - v_E}{v_D} \quad (4.11)$$

In the uniform and isotropic shrinkage model the linear shrinkage is 1/3 of the volumetric shrinkage:

$$S_t = \frac{S_i}{3} \quad (4.12)$$

Process and Geometry Effects on Shrinkage

The effects of packing pressure, melt and mold temperature, and gate thickness are all captured by the PVT method. Packing pressure has the greatest effect on shrinkage, and shrinkage decreases with increasing packing pressure (Figure 4.13). Higher packing pressures force more material into the cavity, resulting in greater expansion of the material as it de-pressurizes relative to the contraction of the material as it cools. Molders will often increase packing pressure to rectify undesirable material shrinkage, although excessive packing pressure can cause greater residual stresses, part warpage, and parts that may actually stick in the mold during ejection.

Figure 4.13: Linear shrinkage as a function of packing pressure

Figure 4.14 shows melt temperature effects on shrinkage. Shrinkage increases with higher melt temperatures. This occurs since the cooling time of the part relative to the cooling time of the gate increases, resulting in gate freeze-off earlier in the molding cycle.

Figure 4.14: Linear shrinkage as a function of melt temperature

Figure 4.15 shows mold temperature effects on shrinkage. Shrinkage decreases with increasing mold temperature since the cooling time of the part relative to the cooling time of the gate *decreases*, resulting in gate freeze-off *later* in the molding cycle. In general the effects of melt and mold temperatures on material shrinkage are much less pronounced than the effect of packing pressure.

Figure 4.15: Linear shrinkage as a function of mold temperature

As the gate size increases, shrinkage decreases (Figure 4.16). As gate size increases relative to the nominal wall thickness, the point in time at which the gate freezes off occurs later in the process, allowing more packing flow through the gate to offset material shrinkage in the cavity. Larger gate sizes can alleviate excessive shrinkage in a part; however this can lead to parts that are more difficult to de-gate. In general, gates are sized to about 80% of the nominal wall thickness.

Figure 4.16: Linear shrinkage as a function of gate size

Limitations of the PVT Method

The PVT method for estimating shrinkage is a uniform (equivalent shrinkage everywhere throughout the part), isotropic (equivalent shrinkage in the inflow, cross-flow, and through-thickness directions) model. In practice, materials exhibit non-uniform, orthotropic shrinkage behavior caused by temperature and pressure gradients across a part during processing and cooling. The PVT method assumes that temperature and pressure are the same everywhere throughout the part and that the gate area experiences the same cooling boundary conditions as the part. In general material shrinkage is greater at locations furthest from the gate, where lower effective pressures inhibit material compensation.

Anisotropic material behavior due to flow orientation and fiber distribution will cause anisotropic material shrinkage. Amorphous unfilled materials exhibit more shrinkage along the flow direction than in the cross-flow direction; in filled materials, material shrinkage is more restrained along the direction of fiber orientation. Mold constraints will also contribute to anisotropic shrinkage, since material prevented from shrinking in one direction will induce greater shrinkage in another direction. The PVT method assumes that the material is free to shrink in all directions, although planned enhancements to the PVT method include orthotropic material modeling that will capture the effects of flow induced orientation.

CHAPTER 5

SYSTEM COST BASED MATERIAL SELECTION

5.1 Introduction

This dissertation focuses on cost as a measure of material selection. As we saw in Chapter 2, most established material selection methodologies use a merit index to rank materials according to their ability to meet the design requirements. The drawbacks to such approaches are two-fold:

- 1) The mapping induced by design requirements or preferences on the candidate material set is either not order preserving, or the mapping from several preferences to a single scale is not intuitive.
- 2) The tradeoffs between design requirements and system cost is not explicit.

This chapter details the cost model for material selection. First this chapter presents the overall cost model, then shows how required tolerance is mapped to part cost. Then, this chapter discusses management of the material performance constraints and optimization of material selection. The last section outlines a procedure for material selection using system-based cost modeling.

5.2 Injection Molding Cost Drivers

5.2.1 Wall Thickness

Nominal wall thickness is perhaps the design variable with the largest effect on cost—cooling time, material volume, achievable flow length, and imbalanced cooling leading to part warpage. The general recommendation is to keep wall thickness as small as possible. Conventionally, wall thicknesses are greater than 2.0 mm, although advanced or leading edge applications are approaching 1.0 mm (GE Plastics, 1995). A thinner nominal wall thickness results in faster cooling times and less material usage; however, this improvement in cost must offset the increased cost of material (for higher performance materials) and the increased difficulty associated with part fillability.

5.2.2 Dimensional Accuracy

The required part tolerance will have a direct impact on part cost; in general, tighter tolerances require greater molding process control and incur higher production costs. However, the material response to process variation will play a large role in meeting part dimensional requirements—amorphous or fiber-filled materials are much less sensitive to process variation.

5.3 Cost as a Material Selection Measure

The cost model, based on an estimated cycle time (from the cooling time calculation) and per part cost based on material cost and part volume, is given below in Equation 5.1:

$$C_T = \underbrace{\frac{(R_{prod})}{3600} t_c}_{\text{Processing Cost}} + \underbrace{V \cdot \rho \cdot C_{mat}}_{\text{Part Cost}} \quad (5.1)$$

where

C_T = total cost of the part (\$/part)

t_c = cycle time for each part (s/part)

R_{prod} = injection molding machine – labor rate (\$/hr)

V = volume of the part (m³/part)

ρ = density of the material (kg/m³)

C_{mat} = cost of the material (\$/kg)

This cost model is an approximation of fixed cost per part, and does not include mold construction costs, mold complexity (e.g., sliders), number of mold cavities, total production run, components of part cycle time due to injection and mold open and closing time, retooling and setup time, colorant, and scrap. Costs of using larger machines to achieve certain flow lengths or to maintain minimum shrinkage values are captured in the R_{prod} variable.

Figure 5.1 shows graphically the cost of achieving an allowable plate deflection against application temperature (fixed edges, distributed load) for three different polymers. The analysis uses the cost equation (Equation 5.1) and CPT with time and temperature flexural modulus dependence. This example illustrates precisely that plate stiffness is a system property; i.e., a function of application requirements, material properties, geometry, and process conditions.

Figure 5.1: Normalized material cost as a function of application temperature

5.4 Mapping Required Tolerance to Cost

A number of factors influence the ability to manufacture injection molded parts that meet dimensional specifications, including error in estimating nominal material shrinkage process variation, mold tool manufacturing tolerances, and even material property variation. In most cases, designers or molders can estimate the nominal material shrinkage and account for it by cutting larger dimensions in the mold steel. Tool dimensional tolerances are usually less than 50% of part tolerances (Malloy, 1994), and high tolerance machining is widely available in the mold tooling industry. Molding quality parts with tight tolerance requirements is more sensitive to the molding process

conditions and their repeatability than to any other factor. Therefore, the key to meeting dimensional tolerances and achieving high part yields is minimizing part to part variation or using materials that are less dimensionally sensitive to process variations.

For the material selection problem, this paper proposes to link tolerance requirements directly to cost. In theory, there are a number of ways to accomplish this; two of them are:

- 1) *Machine–labor rate model*. Tighter tolerances require greater machine control and molder sophistication, and hence higher machine–labor rates.
- 2) *Yield-rate model*. Tighter part tolerances result in lower yields. Molders generally figure a yield rate into their cost structure and adjust this yield rate downward to cover themselves on jobs requiring fine tolerances (often based on their practical experience with a particular material).

This dissertation develops and applies the machine–labor rate model.

Machine–labor Rate Cost Model

For applications requiring tight dimensional control, molders may elect to utilize a more sophisticated injection molding machine (with a commensurably higher labor rate). The machine–labor-rate model captures the effect of higher equipment and labor costs for tight tolerance applications.

This model requires an estimate of process deviations (mold and melt temperatures, packing pressure) for standard and fine tolerance molding processes (Table 5.1), and standard and fine tolerance machine–labor rates, R^{std} and R^{fine} respectively (Table 5.2).

Table 5.1: Process deviations for standard and fine tolerance molding processes[£]

Melt Temperature, $T_{melt} : \delta_{melt}^{std} = \pm 7$ (°C)	Melt Temperature, $T_{melt} : \delta_{melt}^{fine} = \pm 3$ (°C)
Mold Temperature, $T_{mold} : \delta_{mold}^{std} = \pm 7$ (°C)	Mold Temperature, $T_{mold} : \delta_{mold}^{fine} = \pm 3$ (°C)
Packing Pressure, $P_{pack} : \delta_{pack}^{std} = \pm 20$ (MPa)	Packing Pressure, $P_{pack} : \delta_{pack}^{fine} = \pm 10$ (MPa)

[£]Estimate by authors based on published industry data.

Table 5.2: Standard and fine tolerance machine–labor rates (\$/hr)

Machine Type	<25	25-50	50-100	100-200	200-500	500-750	750-1000	1000-2000	2000+
R^{std} [§]	29.46	29.95	34.92	42.55	52.73	77.08	85.00	137.29	180.25
R^{fine} [£]	38.30	38.94	45.40	55.32	71.13	100.20	110.50	151.69	205.76

[§]Custom injection molders' machine-hour rates with operator, profit margin included (Plastics Technology, May 1993).

[£]Estimate by authors based on discussions with industry representatives.

Each injection molded part will have a set of n *target dimensions*, x_j , each with a corresponding *tolerance* t_j (where tolerance is prescribed as say $t_j = \pm 0.010$). Now consider Figure 5.2. Knowing R^{std} and R^{fine} will fix two points on the machine–labor rate—required tolerance curve shown in Figure 3.2, namely, the cost of achieving a fine tolerance Tol_j^{fine} , and the cost for achieving a standard tolerance Tol_j^{std} . Tol_j^{fine} and Tol_j^{std} are not *prescribed* tolerances, but rather *achievable* tolerances for a specific process (standard or fine) and for a specific dimension j .

Figure 5.2: Machine–Labor rate as a function of desired tolerance

For material selection purposes, we would like to know the cost of achieving *any* tolerance. I have chosen to employ a Log fit using the known machine–labor rates at Tol_j^{fine} and Tol_j^{std} :

$$R_j = \begin{cases} A_j \log(t_j) + B_j & \text{for } t_j < Tol_j^{std} \\ R^{std} & \text{for } t_j > Tol_j^{std} \end{cases} \quad (5.2)$$

where

R_j = machine – labor rate

t_j = required part tolerance for a dimension j

Tol_j^{std} = achievable tolerance at the standard process for a dimension j

R^{std} = machine – labor rate for the standard process

A_j, B_j = curve – fit constants derived below in Equation 5.6

Qualitatively, Equation 5.2 captures the notion that tolerances below Tol_j^{fine} (tighter tolerances) are prohibitively expensive. For required tolerances above Tol_j^{std} , (looser tolerances), we set $R_j = R^{std}$.

Examination of the material shrinkage sensitivity to process variation will determine Tol_j^{std} and Tol_j^{fine} , which are unique to each material and each dimension of a part. The procedure is as follows. First, calculate the maximum and minimum linear shrinkage over the process variation using the PVT method. For the fine tolerance process,

$$\begin{aligned} S_{max}^{fine} &= \max \left\{ S_L \left(P_{pack} \pm \delta_{pack}^{fine}, T_{melt} \pm \delta_{melt}^{fine}, T_{mold} \pm \delta_{mold}^{fine} \right) \right\} \\ S_{min}^{fine} &= \min \left\{ S_L \left(P_{pack} \pm \delta_{pack}^{fine}, T_{melt} \pm \delta_{melt}^{fine}, T_{mold} \pm \delta_{mold}^{fine} \right) \right\} \end{aligned} \quad (5.3)$$

A similar calculation determines the maximum and minimum linear shrinkage for the standard tolerance process. Now, calculate the shrinkage deviation ΔS^{fine} and ΔS^{std} :

$$\begin{aligned} \Delta S^{fine} &= \frac{S_{max}^{fine} - S_{min}^{fine}}{2} \\ \Delta S^{std} &= \frac{S_{max}^{std} - S_{min}^{std}}{2} \end{aligned} \quad (5.4)$$

The achievable process tolerances for a given dimension j are:

$$\begin{aligned} Tol_j^{fine} &= x_j \Delta S^{fine} \\ Tol_j^{std} &= x_j \Delta S^{std} \end{aligned} \quad (5.5)$$

The constants A_j and B_j in equation 5.2 are:

$$\begin{aligned}
A_j &= \frac{R^{fine} + R^{std} \left(1 - 2 \log(T_j^{fine} - T_j^{std}) \right)}{\log(T_j^{std}) - \log(T_j^{fine})} \\
B_j &= \frac{R^{fine} - \log(T_j^{fine} - T_j^{std}) R^{std}}{1 - \log(T_j^{fine} - T_j^{std})}
\end{aligned} \tag{5.6}$$

Finally, for material selection purposes, select the largest machine–labor rate required to manufacture a part within specifications; i.e.,

$$\begin{aligned}
R_{prod} &= \max_j(R_j) \\
&= \text{maximum machine – labor rate over the } j \text{ dimensions}
\end{aligned} \tag{5.7}$$

Figure 5.3 shows graphically the cost of tighter tolerances on part manufacturing cost using the results of this section. This example shows that, for finer tolerances, less dimensionally stable materials (semi-crystalline materials) become more expensive to manufacture relative to dimensionally stable materials (amorphous or filled materials).

Figure 5.3: Part cost as a function of required tolerance

5.5 Optimizing Material Selection

Using the standard design optimization model notation of Arora (1989), I will pose the material selection problem in optimization form. The goal is to find an n -vector $\mathbf{x} = (x_1, x_2, \dots, x_n)$ of design variables to minimize a cost function

$$f(\mathbf{x}) = f(x_1, x_2, \dots, x_n) \quad (5.9)$$

subject to the p equality constraints

$$h_j(\mathbf{x}) \equiv h_j(x_1, x_2, \dots, x_n) = 0; \quad j = 1 \text{ to } p \quad (5.10)$$

and the m inequality constraints

$$g_i(\mathbf{x}) \equiv g_i(x_1, x_2, \dots, x_n) \leq 0; \quad i = 1 \text{ to } m \quad (5.11)$$

5.5.1 Design Variables

The choice of variables that describe the design is dependent on the form of the objective function. Meaningful design variables are those that appear in some form in the objective function. For the simple objective function proposed above (Equations 5.1 and 5.8), the design variables are:

$$\mathbf{x} = (x_1, x_2, x_3) = (a, b, h) \quad (5.12)$$

In this formulation I am considering material and process variables as *fixed constants*. I am not free to fix material variables independently; however, since I am considering a finite set of materials, optimization of the geometry for each material (and corresponding set of material properties) and then selecting the material with the lowest cost is sufficient. Process variables *do* appear in the objective function, and in the present formulation I could optimize the objective function with appropriate inequality constraints on the process variables. However, in practice it is recommended to keep the process window as wide as possible.

5.5.2 Objective Function

The objective function must explicitly capture the effects of the design variables. The cost function of Equation 5.8 (in explicit form) is:

$$f(\mathbf{x}) = \frac{(C_{mach} + C_{labor})}{3600} \frac{\ln \left[\frac{4}{\pi} \left(\frac{T_m - T_w}{T_c - T_w} \right) \right]}{\alpha \pi^2} h^2 + ab \rho C_{mat} h \quad (5.13)$$

5.5.3 Equality and Inequality Constraints

Equality constraints reduce the feasible design space since they eliminate degrees of freedom. Inequality constraints, conversely, enlarge the feasible design space (and generally make for more interesting optimization problems). In the present example, I consider the length and width of the flat plate to be *equality* constraints; i.e., the boundaries of the flat plate are fixed to length A and to width B :

$$\begin{aligned} h_1 &= a - A = 0 \\ h_2 &= b - B = 0 \end{aligned} \quad (5.14)$$

The inequality constraints involve only the plate thickness h . For example, the plate must not exceed an allowable deflection δ_{max} under a prescribed uniform load P_0 with fixed edge conditions, operating temperature T_{env} , and time t_{creep} . This inequality constraint is expressed as

$$g_1 = -h + \sqrt{\frac{\alpha(a,b)P_0b^4}{E_{eff}\delta_{max}}} \leq 0 \quad (5.15)$$

And, the allowable stress σ_a of the material must not be exceeded:

$$g_2 = -h + \sqrt{\frac{\beta_1(a,b)P_0b^2}{\sigma_a}} \leq 0 \quad (5.16)$$

For a consistent system, the number of equality constraints must be less than or equal to the number of design variables, i.e., $p \leq n$. There is no restriction on the number of inequality constraints. For feasible designs, some inequality constraints may be strictly satisfied (*inactive*) or satisfied at equality (*active*). For the case above, in general either the allowable deflection or the allowable stress will determine h .

5.5.4 Solution and Discussion

The solution to the system of Equations 5.12–5.16 is straightforward since there is only one degree of freedom and since the cost function is a monotonically increasing function of h . By inspection, the minimum h that satisfies both g_1 and g_2 yields an optimum design. Of course, more meaningful material selection relies on additional performance models, together with a wider set of design variables, a corresponding constraint set, and applicable cost function. For illustration, I have listed possible performance models, inputs, outputs, and effect on cost in Table 5.3 below.

Table 5.3: Mechanical and Manufacturing Performance Models

Classical Plate Theory (CPT)	h, a, b	$P, T_{env}, t_{creep}, E_{eff}, \nu$	$\delta_{max}, \sigma_{max}$	V, t_{cycle}, L_f
CPT w/ Orthotropic Modulus	h, a, b	$P, T_{env}, t_{creep}, E_{eff}, \nu, E_1, E_2$	$\delta_{max}, \sigma_{max}$	V, t_{cycle}, L_f
Rayleigh-Ritz Energy Method	h, a, b, w, ℓ, r	$P, T_{env}, t_{creep}, E_{eff}, \nu$	$\delta_{max}, \sigma_{max}$	V, t_{cycle}, L_f
Impact Model	h, w, r	$P, \dot{\epsilon}, \sigma_1/\sigma_y$	<i>brittle/ductile failure</i>	V, t_{cycle}, P_{pack}
Fatigue Model	h, w, r	$P, \sigma_{max}, f, T_{env}$	N_f	V, t_{cycle}, P_{pack}
1-D Cooling Model	h	T_m, T_u, T_e, k, c	t_{cycle}	t_{cycle}
1-D Radial Flow	h	T_m, T_u, P_{inj}, μ	L_f	<i>tool complexity,</i> P_{inj}, t_{cycle}
1-D Shrinkage	h, h_R	$T_m, T_u, P_{inj}, k, c,$ <i>PVT properties</i>	S_v	$P_{pack}, t_{cycle},$ <i>part to part variation</i>

This dissertation addresses optimization of material selection for injection molded thermoplastics. However, expanding the universe of discourse to a much wider set of engineering materials and appropriate processes is a worthwhile goal. Since the complete set of potential material, process and geometry combinations is large, such an approach will benefit from a screening of suitable material and process combinations. Ishii, et al. (1991) describe a compatibility-based approach to process selection that uses qualitative information about mechanical properties, part shape, part size, tolerances and surface finish, materials, time to market, production quantity, and production rate. A similar approach that recognizes that some design requirements are *system properties* can narrow the set of candidate solutions with less chance of eliminating potentially more optimal solutions.

CHAPTER 6

APPLICATION: INKJET PRINTER COMPONENTS

6.1 Introduction

This chapter applies system cost-based material selection to components of an inkjet printer. The primary application requirements for computer equipment components are flexural stiffness, ability to pass a UL flammability rating, UV stability, aesthetics, creep resistance on large unsupported spans, and resistance to common cleaners. For most desktop computers impact requirements during use are not stringent, but the boxed printer must withstand a drop-test from 30 inches. The typical operating temperature can vary from 20°C to 35°C, but during shipment, temperatures may reach 45°C.

6.2 Printer Base

Background

The printer base, illustrated in Figure 6.1, provides a platform for the printer subassemblies and printer case. We will model the printer base as a flat plate under a distributed load of 0.7 kPa based on the mass of the printer components (Figure 6.2). We assume fixed edges since the edges of the plate interlock with the printer cover and since the four corners of the base are supported by rubber friction pads. The allowable

deflection at the center of the plate is 1.5 mm. The tolerance requirements for this component are lenient: 23.5 cm $\pm$ 2.0 mm for attachment holes oriented along the long sides. The current design parameters are shown in Table 6.1. Figure 6.2 shows the loading conditions and geometry assumptions for the printer base.

Table 6.1: Printer base current design

Current material	ABS
Nominal wall thickness (mm)	3.0
Part mass (kg)	0.420
Maximum application temperature (°C)	45
Loading time at this maximum temperature (hrs)	100
Maximum allowable deflection at center (mm)	1.5
Maximum dimension & required tolerance (cm $\pm$ mm)	23.25 $\pm$ 2

Figure 6.1: Printer base

Figure 6.2: Flat plate model and loading for the printer base

Preliminary Material Screening

For this class of applications, ABS, ABS/PC, and PC (both filled and unfilled) are typical candidates since they satisfy the flammability and UV requirements, and possess good aesthetics and colorability.

Application Temperature

The cost of meeting these application requirements as a function of operating temperature is shown graphically in Figure 6.3. The figure shows that for operating temperatures up to about 45 °C, the ABS (KJC) is the superior choice. Above 45 °C, 10% glass filled PC is more cost effective. The data plotted in Figure 6.3 are for a creep test time of 100 hours, and a tolerance requirement of 23.25 cm $\pm$ 2 mm.

Figure 6.3: Cost as a function of temperature for the printer base

Creep Test Time

Figure 6.4 shows the same materials plotted as a function of tested creep time at an application temperature of 45°C. For tested creep times up to 250 hours, the ABS (KJC) is the superior choice. Above 250 hours, the 10% glass-filled PC is more economical. The curves for the two filled PC materials do not vary with tested creep time due to the recommended practice of attenuating extrapolated creep moduli that are greater than the recorded nominal material modulus.

Figure 6.4: Cost as a function of creep test time for the printer base

Tolerance Requirements

Cost as a function of required tolerance for the printer base is shown in Figure 6.5. As mentioned above, the tolerance requirements for this application are 23.5 cm $\pm$ 2.0 mm. Above the required tolerance of $\pm$ 0.50 mm shown in Figure 6.5 there is no change in material preference. However, there are decision points at tighter tolerances; e.g., the ABS/PC blend (C2950) becomes a more attractive choice than the ABS (KJC) below $\pm$ 0.1 mm required tolerance.

Figure 6.5: Cost as a function of required tolerance for the printer base

An Alternate Material Class

The above analysis included several thermoplastics traditionally used in standard business component housing applications. The inkjet printer market is fiercely competitive, and the vendor would like to reduce material costs wherever feasible. Figure 6.6 shows cost as a function of application temperature for the printer base, now including high impact polystyrene (HIPS), which has a much lower cost than the materials used in the preceding analysis throughout a broad application temperature range. The data for Figure 6.6 uses the application requirements listed in Table 6.1.

Figure 6.6: Cost as a function of application temperature, including high impact polystyrene

Printer Base Material Selection Summary

Table 6.2 shows a summary of the material selection results for the printer base. For the application temperature of 45°C at a creep test time of 100 hours, the high impact polystyrene is an attractive choice except that the impact behavior of HIPS is much worse than the other materials. However, using HIPS, at about 25% of the cost of the current material, provides plenty of margin for configuring the rough and detailed geometry in such a way to minimize stress concentrations and other impact concerns. The vendor is now considering HIPS as a replacement material for the printer base.

Table 6.2: Material selection summary for the printer base

	Aluminum 6061-T6	Aluminum 7075-T6	Steel A36	Steel 4140	Steel 4340	Steel 52100
Material Cost [\$ /kg]	4.48	4.98	5.20	5.47	8.36	1.36
Manufacturing Cost [\$ /part]	0.19	0.26	0.20	0.15	0.10	0.16
Total Cost [\$ /part]	2.05	2.36	2.14	2.05	2.59	0.53
Modulus [MPa]	2480	2275	2690	2650	7580	2413
Thickness [mm]	3.3	3.4	3.2	2.9	2.1	2.62
Achievable Tolerance [$\pm$mm]	0.51	0.46	0.49	0.49	0.40	0.50
Notched Impact Strength [J/m]	214	187	427	534	107	93

6.3 Printer Chassis

Background

The printer chassis (Figure 6.7) provides the structural foundation for the printer. The printer carriage assembly, containing the printing mechanism, fastens directly to the printer chassis. Since the print-head must translate accurately at high speeds, stiffness of the printer chassis is the primary functional concern. Table 6.3 details the current printer chassis material selection.

The printer chassis cannot be modeled as a flat plate, so this example will use the equivalent stiffness method (Section 4.2.3) to approximate the load—deflection relationship implicit in the existing printer chassis design. This will permit comparing the current material choice with other materials possessing the same system stiffness.

Table 6.3: Printer chassis current material selection.

Current Material	PC; 20% glass fibers; 5% glass beads
Nominal wall thickness (mm)	3.0
Part Mass (kg)	0.475
Maximum application temperature (°C)	45
Loading time at this maximum temperature (hrs)	100
Maximum dimension & required tolerance (cm ±mm)	36 ±1

Figure 6.7: Printer chassis

Preliminary Material Screening

The primary material properties of interest in the printer chassis are system stiffness, dimensional stability, impact toughness, a V-0 UL flammability rating, and UV resistance. Material families that meet these general requirements include ABS/PC Blends, PC, PBT, and PPE + PS Blends. The next sections show the relative performance of several representatives of these polymer families with respect to application temperature, tested creep time, and required tolerance. The current choice, for reference purposes, is approximated by 30% glass filled PC.

Application Temperature

The cost of meeting the printer application requirements is shown graphically in Figure 6.8, normalized to the lowest cost material for a creep test time of 100 hours (normalized cost = 1.0). This figure shows that for operating temperatures up to about 95 °C, the 30% glass/mica filled PPE + PS blend is the superior choice. Above 95°C, the 30% glass filled PBT becomes more attractive. The current choice (30% glass filled PC) incurs about a 36% higher system cost for an equivalent system stiffness.

Figure 6.8: Normalized cost as a function of temperature for the printer chassis

Creep Test Time

Figure 6.9 shows the same materials plotted as a function of tested creep time (at an application temperature of 45 °C). This figure illustrates no change in optimum material for tested creep times up to 1000 hours, and again the 30% glass/mica filled PPE + PS blend is the superior choice.

Figure 6.9: Normalized cost as a function of creep time for the printer chassis

Tolerance Requirements

Cost as a function of required tolerance for the printer chassis is shown in Figure 6.10. Throughout the range of required tolerances up to ± 1.5 mm, the 30% glass/mica filled PPE + PS blend is the superior choice.

Figure 6.10: Normalized cost as a function of required tolerance for the printer chassis

Printer Chassis Material Selection Summary

Table 6.4 shows a summary of the material selection results for the printer chassis. For the application temperature of 45°C and a creep test time of 100 hours, the 30% glass/mica filled PPE + PS is an attractive choice. The notched impact behavior of the filled PPE + PS is not much lower than the current choice (91 J/m versus 107 J/m), and has a 26% lower system cost.

Table 6.4: Material selection summary for the printer chassis

	Aluminum 6061-T6	Aluminum 7075-T6	Aluminum 7050-T6	Aluminum 7050-T6	Aluminum 7050-T6	Aluminum 7050-T6
Material Cost [\$ /kg]	8.77	6.90	5.20	6.39	5.84	6.48
Manufacturing Cost [\$ /part]	0.18	0.36	0.60	0.24	0.18	0.15
Total Cost [\$ /part]	4.29	4.20	4.47	4.07	3.74	3.12
Modulus [MPa]	7584	3447	2690	6894	7584	7584
Thickness [mm]	3.0	3.9	5.6	3.3	3.2	3.1
Achievable Tolerance [$\pm$mm]	0.61	0.71	0.67	0.63	0.67	0.83
Notched Impact Strength [J/m]	107	107	427	85	80	91

CHAPTER 7

APPLICATION: AUTOMOTIVE COMPONENTS

7.1 Introduction

This chapter applies system cost-based material selection to two automotive components—a Heating/Venting/Air Conditioning (HVAC) housing and an undercarriage battery pack housing for a hybrid-powered vehicle. Application requirements for automobile components can vary widely, so they will be discussed individually for each application.

7.2 HVAC Housing

Background

The HVAC housing (Figure 7.1) provides a means for controlling the ambient temperature of an automobile interior and directs the flow of conditioned air between temperatures of -20°C to 45°C. The HVAC housing also provides structural containment of the internal HVAC components, including the heater core (which contains 120°C engine coolant), the evaporator core (which contains refrigerant at 10°C), and several airflow dampers. The HVAC housing also provides structural mounting surfaces for

various external components, including damper actuators, an air blower unit, and several wiring harnesses. Table 7.1 details the current HVAC housing material selection.

Table 7.1: HVAC housing current design

Current Material	PP 20% Talc Filled
Nominal wall thickness (mm)	2.5
Part Mass (kg)	1.24
Maximum application temperature (°C)	65
Loading time at this maximum temperature (hrs)	1000
Maximum dimension & required tolerance (cm ±mm)	91 ±5

The HVAC housing cannot be modeled as a flat plate, so this study uses the equivalent stiffness method to approximate the load—deflection relationship implicit in the existing HVAC housing design, allowing examination of the relative system performance between the current material choice (20% talc-filled polypropylene) and prospective materials.

Figure 7.1: HVAC system

Preliminary Material Screening

The primary material application requirements of the HVAC housing are moderate stiffness under a range of temperatures and good resistance to automotive fluids. The current material is polypropylene, which exhibits resistance to a wide variety of chemicals. Other polymer families that typically perform well in this area are PBT, PPE/PA blends, and HIPS. The next sections show the relative performance of several members of these polymer families with respect to application temperature, tested creep time, and required tolerance.

Application Temperature

The cost of meeting the HVAC housing requirements is shown graphically in Figure 7.2. These curves represent the cost of each material to meet the same system stiffness provided by the talc-filled polypropylene across a range of application temperatures. Figure 7.2 shows that for operating temperatures up to about 95°C, HIPS is the superior choice. Above 95 °C, the 20% talc-filled polypropylene (the current choice) becomes more attractive. This reflects the fact that polypropylene performs better at higher temperatures than high-impact polystyrene.

The data plotted in Figure 7.2 are for a creep test time of 1000 hours, which reflects continuous loading and is the maximum creep test time recommended for analysis based on the available creep data. The target application temperature is 65°C.

Figure 7.2: Cost as a function of temperature for the HVAC housing

Creep Test Time

Figure 7.3 shows the same materials plotted as a function of tested creep time (at the maximum application temperature of 65 °C). This figure shows no change in the relative ordering of the materials. For the entire range of tested creep times shown, HIPS is the superior choice.

Figure 7.3: Cost as a function of creep test time for the HVAC housing

Tolerance Requirements

Cost as a function of required tolerance for the HVAC housing is shown in Figure 7.4. The tightest tolerance requirements on the housing are on the mounting holes along the length dimension of the case halves (91 cm). The required tolerance for this dimension is ± 5 mm (in order to mate the two halves of the HVAC housing). Throughout the range of required tolerances shown in Figure 7.4, HIPS is the superior choice. In fact, the tolerance requirements for this application are not stringent, and the base material costs differ enough that the application tolerance requirements induce no order change.

Figure 7.4: Cost as a function of required tolerance for the HVAC housing

Automobile HVAC Material Selection Summary

Table 7.2 shows a summary of the material selection results for the HVAC housing. For the application temperature of 65°C, a creep test time of 1000 hours, and a required tolerance of ± 5 mm on 91 cm, the high-impact polystyrene is an attractive choice. The notched impact behavior of the HIPS is greater than the current choice (64 J/m versus 37 J/m), but the HIPS part has a 31% lower estimated system cost.

Table 7.2: Material selection summary for the HVAC housing

	Aluminum	Steel	Carbon Fiber	FRP	CFRP
Material Cost [\$ /kg]	2.20	4.85	6.39	5.73	1.36
Manufacturing Cost [\$ /part]	0.27	0.15	0.14	0.19	0.27
Total Cost [\$ /part]	3.71	5.10	6.61	6.69	2.55
Modulus [MPa]	2000	7500	6900	2250	3300
Thickness [mm]	2.5	1.1	1.1	1.7	2.30
Achievable Tolerance [$\pm$mm]	1.86	1.48	1.40	1.70	1.87
Notched Impact Strength [J/m]	37	85	85	240	64

7.3 Battery Pack Housing

Background

The battery pack housing (Figure 7.5) will support a set of batteries for a hybrid-powered vehicle. The housing will mount to the undercarriage of the vehicle and support a total load of 70 kg ($686.7 \text{ N} = 1.39 \text{ kPa}$ distributed load). The battery pack housing is modeled as a flat plate with fixed edges and the maximum allowable deflection at the center is 5 mm.

Table 7.3: Battery pack housing design requirements

Distributed load (kPa)	1.39
Maximum application temperature ($^{\circ}\text{C}$)	65
Loading time at this maximum temperature (hrs)	1000
Maximum allowable deflection at center (mm)	5
Maximum dimension & required tolerance (cm $\pm$mm)	80 $\pm$5

Figure 7.5: Five-sided box model and loading for the battery pack housing

Preliminary Material Screening

The primary material application requirements of the battery pack housing are high stiffness under a range of temperatures and good resistance to automotive fluids. Two polymer families that typically perform well in this area are PBT and PBT/PC blends. The next sections show the relative performance of several members of these polymer families with respect to application temperature, tested creep time, and required tolerance.

Application Temperature

The cost of meeting the battery pack housing requirements is shown graphically in Figure 7.6. These curves represent the cost of each material to meet the application requirements across a range of application temperatures. For the operating temperatures shown in the figure, 30% glass-filled PBT is the superior choice.

The data plotted in Figure 7.6 are for a creep test time of 1000 hours, which reflects continuous loading and is the maximum creep test time recommended for analysis based on the available creep data. The target application temperature is 65°C.

Figure 7.6: Cost as a function of application temperature for the battery pack housing

Creep Test Time

Figure 7.7 shows the same materials plotted as a function of tested creep time (at the maximum application temperature of 65 °C). This figure shows no change in the relative ordering of the materials. For the entire range of tested creep times shown, the 30% glass-filled PBT is the superior choice.

Figure 7.7: Cost as a function of tested creep time for the battery pack housing

Tolerance Requirements

Cost as a function of required tolerance for the battery pack housing is shown in Figure 7.8. The tightest tolerance requirements on the housing are on the mounting holes (not shown) along the edge of the length dimension of the box (80 cm). The required tolerance for this dimension is ± 5 mm. Throughout the range of required tolerances shown in Figure 7.8, the 30% glass-filled PBT is the superior choice. As in the HVAC example above, the tolerance requirements for this application are not stringent, and the base material costs differ enough that the application tolerance requirements induce no order change.

Figure 7.8: Cost as a function of required tolerance for the battery pack housing

Battery Pack Housing Material Selection Summary

Table 7.4 shows a summary of the material selection results for the battery pack housing. For the application temperature of 65°C and a creep test time of 1000 hours, the 30% glass-filled PBT is the low-cost choice.

Table 7.4: Material selection summary for the battery pack housing

	1	2	3	4	5	6	7
Material Cost [\$/kg]	6.11	4.85	6.39	5.84	6.39	5.53	5.40
Manufacturing Cost [\$/part]	1.94	0.71	0.53	0.45	0.80	1.34	0.69
Total Cost [\$/part]	67.27	33.90	43.76	43.08	46.83	47.19	40.93
Modulus [MPa]	2050	7500	6900	7600	5050	2250	5400
Thickness [mm]	8.7	4.9	4.6	4.8	5.1	7.4	5.6
Achievable Tolerance [$\pm$mm]	1.85	1.47	1.40	1.49	1.03	1.13	1.48
Notched Impact Str. [J/m]	534	85	85	80	53	800	170

CHAPTER 8

DISCUSSION

8.1 Introduction

This chapter discusses the results of this dissertation. The first section reviews the factors that influence material selection. The next section discusses the implications of the case studies. Then this chapter reviews the challenges to the current implementation.

8.2 Factors Influencing Material Selection

The factors affecting choice of material can be classified in two ways—those properties that belong only to the material, and are not influenced by amount of material, geometry, or process; and, those properties that belong to the system and *are* influenced by amount of material, geometry, or process.

8.2.1 Material Properties

- 1) *Chemical Resistance.* Compatibility with application environmental chemical exposure often strongly influences the class of materials suitable for a particular application. Typically, the chemical compatibility of a material is not influenced by the size of the part, although oversized parts may have reduced stresses and limit the sensitivity of the polymer to attack by certain chemicals.

- 2) *UV Resistance.* Materials which do not degrade or degrade only slowly over time are sometimes an important application requirement. Gamma radiation can also degrade certain polymers, and certain grades of polymers are available that resist degradation due to gamma radiation.
- 3) *Agency Approval.* The U.S. Food and Drug Administration (FDA) and National Sanitation Foundation (NSF) must approve specific materials for certain applications. These are just two agencies that require material qualification; there are others.

8.2.2 System Properties

- 1) *Required stiffness.* Determines required thickness for a given material and allowable deflection. The stiffness calculations are based on a flat plate geometry with various boundary and loading conditions. There are similar closed-form solutions for other simple geometries, but in many cases the stiffness problem must be solved by other approximate means, such as the equivalent stiffness method.
- 2) *Application temperature and time dependent behavior.* Higher temperatures and long term loadings will decrease the apparent material modulus. In general, under increased temperature and loading time, a part will require a greater thickness to achieve an equivalent stiffness.
- 3) *Achievable flow length.* Limits minimum thickness. For instance, to fill the part using only one gate, each material will have a minimum thickness required to adequately fill the part. The material selection methodology uses disk filling simulations to calculate achievable flow lengths.
- 4) *Cooling time.* Directly impacts manufacturing cost. The cooling time is proportional to the part thickness (squared), and to a lesser extent the processing conditions and material properties. This dissertation uses a closed-

form approximation of the solution to the 1-D heat equation for a flat plate as an estimation of cycle time.

- 5) *Yield strength*. Limits the minimum thickness of the plate.
- 6) *Fatigue strength*. Limits maximum allowable stress
- 7) *Required Tolerance*. Directly impacts manufacturing cost. Tighter tolerances will incur greater costs when the dimensional stability of the thermoplastic exceeds the process control of the injection molding machine. This dissertation uses the PVT method to calculate a uniform, isotropic shrinkage. Estimations of process variation and machine labor-rates for standard and fine processes are used to estimate achievable tolerances and resulting manufacturing cost for a given material.
- 8) *Flammability*. For certain applications, resistance to burning and combustion is desired. Underwriter's Laboratory has designed a rating scheme and test procedure that measures a plastics ability to resist burning. This rating is dependent upon specimen thickness. A particular material may have different ratings for different thicknesses, but in general a material will only have one or two thickness/ratings listed. The flammability rating limits minimum wall thicknesses in some cases.

8.3 Implications of the Case Studies

- 1) *Sensitivity to performance requirements*. The case studies examined estimated part cost a function of application temperature, tested creep time, and required geometric tolerance. System cost is most sensitive to application temperature requirements, and application temperature induces a change in the optimum material due to the wide range of sensitivity of material stiffness to operating temperature. Part cost is less sensitive to long term loading requirements. Loading time will induce a change in the optimum material, primarily if two

materials have similar system costs. System part cost showed the least sensitivity to tolerance requirements, primarily due to the fact that for the case study examples, tolerance requirements were not stringent.

- 2) *Agreement with expected results.* In the case studies, the optimum materials were typical of the commonly used materials for the particular applications. For the inkjet printer base, an alternate material was proposed (high-impact polystyrene; HIPS) because of its relatively high performance at low system cost. The vendor is currently considering HIPS as a replacement material. With full characterization of polymer families and grades, several more viable material candidates may arise. However, due to the risks involved in using a new material, closer examination of the material performance in actual prototype parts will probably be necessary.
- 3) *Capturing all the application requirements.* The material selection system proposed in this dissertation considers stiffness, strength, dimensional stability, impact and fatigue. Of these, impact and fatigue behavior are the least well understood. For applications with strict performance requirements in this area, more detailed analysis is required. In addition, detailed geometry will induce certain local performance effects (e.g., stress concentrations); to some extent, this effect can be alleviated by properly tailoring the detailed geometry. In some cases this is unavoidable, and the geometric evaluation used in the current system cannot discriminate materials on this level.
- 4) *Capturing all the cost drivers of injection molding.* Part thickness, material volume, and material cost contribute the most to system part cost. In the current system these costs are captured, however tooling costs are not considered. In many cases, tooling cost will not induce a change in material preference. Also, improper part design can incur larger processing cost due to lower part yields. Tolerance requirements are captured in the material selection system, but costs due to imbalanced cooling, imbalanced flow, and large

changes in wall section thickness are not captured. These can be avoided in properly designed parts, but some materials respond more robustly to such conditions. This is not captured in the material selection cost model.

8.4 Continuing Challenges

- 1) *Performance model evaluation.* Fatigue, impact, and ultimate strength evaluation require calculating maximum stress states. This is usually a strong function of geometric features, which are not generally considered in the simpler, closed form equations. FEM analysis can yield detailed results, but usually requires more time and personnel resources. The performance model evaluation techniques must strike a balance between accuracy of results and ease of implementation. However, it may be feasible to include more sophisticated solution techniques without requiring much additional geometric or material data.
- 2) *Material candidate pruning.* The essence of this proposed approach is that some selection criteria are *system* properties, i.e., functions of the geometry and material properties. However, many selection criteria are not; e.g., chemical and UV resistance, hardness or abrasion resistance, flame retardance or FDA approval. A comprehensive plastic material selection system should provide a means of screening materials for non-system based requirements.
- 3) *Oversimplified geometries.* Oversimplified geometries used for the mechanical and processing performance models may fail to effectively capture the system performance properties. Ways to make this method more applicable include extending the class of geometries (e.g., there are many compiled equations for stress and strain available in the literature); using more general solution techniques—e.g., finite difference or finite element methods. I listed as one of the benefits of this approach the ability to examine advanced performance issues without resorting to detailed FEM. However, there now exists simplified

FEM packages (both structural and flow simulation) that can act as black-box functions in terms of determining stress and strains, flow lengths, etc. However, the problem then becomes more one of software implementation than systematic methodology. A reasonable short term goal is to eliminate the truly non-optimal material candidates while not eliminating potentially optimum candidates.

- 4) *Acquiring material data.* The material selection system uses material data that in some cases is not readily available, especially for commodity materials. Characterization of materials across all polymer families and most grades is needed to perform adequate system cost based material selection. In lieu of this information, the best approach is use materials typical of the application. This may not result in optimum material selection, but may avoid costly field failures and engineering fixes during part production.

CHAPTER 9

CONCLUSIONS

9.1 Summary

9.1.1 The Material Selection Problem

In selecting a material for a particular application, the primary challenge is meeting multiple design objectives including strength, stiffness, durability, and light-weight, and usually at the lowest possible cost. With sufficient time and resources, this can be accomplished fairly easily; however, increasing pressures for faster times-to-market don't allow designers the luxury of examining thoroughly the virtually limitless choices of material, process, and geometry. This dissertation has focused on using simplified system performance models that allow designers to quickly narrow the candidate set of injection molded engineering thermoplastic materials, permitting the designer to focus scarce resources on the few most viable candidates.

9.1.2 Existing Material Selection Approaches

Of course, designers have been producing high-quality, functional thermoplastic parts for many years. The primary ingredient in most successful design and material selection is experience and historical knowledge. There are established systematic approaches to

material selection, and these approaches can be grouped into four major categories: property ranking approaches, knowledge-based approaches, application-based approaches, and system performance-based approaches. The system cost based approach outlined in this dissertation is a performance based approach.

9.1.3 System Cost Based Material Selection

The primary drawback to most systematic approaches is that they do not provide a means of explicitly examining the tradeoffs between meeting performance requirements and the resulting system cost. This dissertation proposes a material preference scheme based on mechanical and manufacturing performance models that map design requirements directly to manufactured part cost. These mechanical and manufacturing performance models include:

- 1) System stiffness
- 2) Achievable flow length
- 3) Cooling time
- 4) Yield strength
- 5) Fatigue strength
- 6) Required tolerance

The advantage of such an approach is that it allows the user to examine the tradeoffs between application requirements and resulting material ranking.

9.1.4 Material Selection Case Studies

This dissertation uses four application example applications to validate the system cost based material selection approach. These examples include two computer printer components, and two automotive components. Table 9.1 summarizes the implications of the material selection case studies.

Table 9.1: Summary of implications of the material selection case studies

Printer Base	Flat plate	Of conventional thermoplastics, showed that current base material was most cost-effective. Also showed that an alternative material is potentially more cost effective.
Printer Chassis	Equivalent Stiffness	Showed how to apply the method to more complex geometries using the equivalent stiffness method.
HVAC Housing	Equivalent Stiffness	Again showed how to apply the method to more complex geometries using the equivalent stiffness method.
Battery Pack Housing	Flat plate	Showed how basic requirements can prescreen material candidates using simple flat plate equations.

9.2 Contributions

The direct contributions of this work include:

- 1) Systematic approach to cost based material selection for engineering thermoplastics. The material selection procedure proposed in this dissertation evaluates materials based on system part cost. No other currently published material selection system evaluates candidate materials in this fashion.
- 2) Insight into the interaction between material, process and geometry. System cost based material selection permits the examination of system cost as a

function of application requirements, allowing the designer to directly observe the costs of meeting application requirements.

- 3) A computerized decision support tool. The case study analyses were performed using a computer software program that evaluated the mechanical and processing performance models. The calculations can be performed by hand, however, evaluation of a large set of candidate materials lends itself well to computerized analysis.
- 4) A material selection approach that results in a lower overall component cost and quicker time-to-market. System cost based material selection can quickly generate a small set of economically viable material candidates, allowing the designer to focus capital resources in a more cost-effective manner.

9.3 Future Work

There are many ways in which this material selection methodology can be enhanced. I summarize these below:

- 1) *Determining a global optimum.* This system considers only injection molded thermoplastic materials. Thermoplastic manufacturing processes alone are numerous, and in fact developed because they can provide a lower overall cost for component manufacturing for certain applications. A system that considers many process and material combinations, as well as secondary operations, would be a step in the right direction. Such a system would need a method of screening potential candidates to yield a manageable set (e.g., the methods of Ashby, 1992, and Ishii, et al., 1991). An implementation challenge is the integration and application of suitable performance models.
- 2) *Additional performance models.* One benefit of this approach is the ability to quite easily extend the approach by improving the existing models or adding

new models. Examples include improved impact and fatigue models, more comprehensive material flow models, and more general stress and deflection models. Of course, some of these models require more detailed material characterization, which is already a limitation in the current scheme.

- 3) *Include more geometries.* Another limitation of the current system is the inability to handle arbitrary geometry. Simple geometries provide the advantage of quickly modeling system behavior, but the range of geometry and loadings typical of commercial parts limits the applicability of simple closed form solutions. An integrated, simplified FEA solver could handle more general geometries.
- 4) *Systematic candidate material screening.* The case studies shown in this dissertation assumed a knowledge of typical materials suitable for the particular application. Experienced designers may have the ability to effectively screen materials, but inexperienced designers don't have this luxury. A system that provided a set of candidate materials based on chemical compatibility requirements, UV requirements, flammability requirements, agency requirements, etc. A previous application and material selection library may also augment the material pre-selection task.

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