

“VALUE SOURCING” IN SUPPLY CHAINS

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By

Kuntal Bhattacharyya
Dept. of Management and Information Systems
Kent State University

Dissertation Committee:

Dr. Alfred L. Guiffrida (Chair)
Dr. Murali Shanker
Dr. Michael Hu

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**I can fly higher than an eagle...
Coz...you are the wind beneath my wings.**

~ Bette Midler

~ *To my wife, Shikha.*

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CHAPTER 1

INTRODUCTION

1.1. Background

The business landscape over the past couple of decades has been characterized by intense global competition, increasingly demanding customers, and shortened product life cycles. The fast-paced just-in-time (JIT) manufacturing environment has offered little inventory to cushion production or scheduling problems, therefore forcing manufacturers to realize the benefit and importance of strategic buyer-supplier relationships. Thomas and Griffin (1996) reviewed the literature involving coordinated planning between two or more stages of a supply chain from the years 1960-1994, and grouped them into three distinct categories: buyer-vendor coordination (procurement of the material), production-distribution coordination (transformation of material into finished goods), and inventory-distribution coordination (distribution of these finished goods to customers).

The philosophy of supply chain management emerged as manufacturers experimented with strategic partnerships with their immediate suppliers to stay in a competitive market, where the mode of competition gradually shifted from between firms to between supply chains (Christopher, 1998). The evolution of supply chain management continues in the twenty-first century as organizations extend best practices in managing responsive supply chains to provide value to the end customer (Ketchen et al., 2008). Effective sourcing is a key element in facilitating responsive supply chains (Swafford et al., 2006). The problems faced by Sony when launching the Playstation3 illustrate the importance of effective sourcing. In May 2006, Sony said it would have 2 million PlayStation3 consoles available for the holiday-buying season.

However, in November it had only 400,000 game players ready, due to the shortage of a console's blue-ray DVD player included in the package. Consequently, Sony's stock prices fell, resulting in increased competition due to Sony's ineffective sourcing strategies.

An ongoing challenge in responsive supply chains is to reduce costs while continuously improving customer service levels. Providing "value" to the customer is a difficult component of this challenge as customers continue to demand high quality sustainable products delivered at their door in minimum time and at a minimum cost. This dissertation defines value sourcing as "the process of procuring goods and/or services to meet the needs of the customer via a set of customer-focused supply management initiatives that enables an organization in the selection and management of suppliers", and focuses on how sourcing contributes to value in a supply chain. We propose *value sourcing* as a prerequisite for establishing responsive supply chains in today's competitive global landscape.

1.2. Strategic Position of Value Sourcing in Supply Chain Management

Supply chain management (SCM) remains a topic of considerable interest among supply practitioners and academicians. In the past fifteen years, in line with the interest in SCM, academic journals have been created or renamed, business schools have offered new SCM programs, and B-School professors have altered their titles and research interests. We begin this discussion with a candid snapshot of SCM vs. purchasing and where value sourcing fits therein.

Purchasing has traditionally been seen as an upstream approach where the buyer is only concerned with the procurement of a product or commodity from its "upstream" supply. Kraljic (1983) is widely considered as the driving force behind the marriage of purchasing and supply management. To facilitate this marriage, Larson and Halldorsson (2002) discuss four conceptual

perspectives on purchasing vs. supply chain management: traditionalist, relabelist, unionist, and intersectionist. *Traditonalists* conceived SCM as a strategic aspect of purchasing; *relabelers* simply changed the name of purchasing to SCM; *unionists* saw purchasing as part of SCM; finally, *intersectionists* viewed SCM as not a mere union, but a cross-functional effort between purchasing and SCM (Figure 1a). In line with these developments in SCM, Christopher (1998) first provided an overarching definition of SCM as “the management of upstream and downstream relationships with suppliers and customers to deliver superior customer value at less cost to the supply chain as a whole”, thereby portraying a unionist view that sees purchasing as part of SCM, where SCM subsumes purchasing.

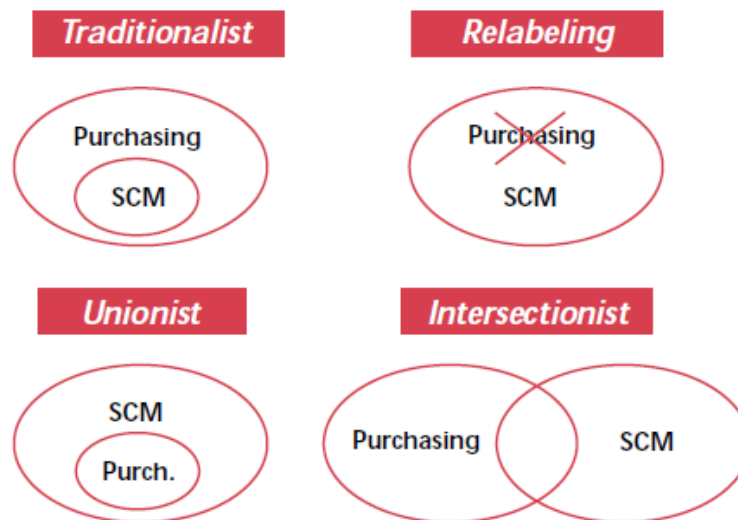
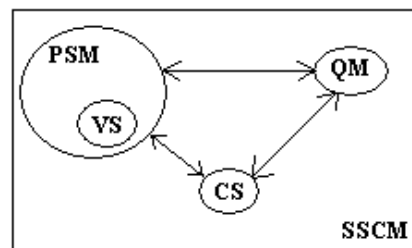


FIGURE 1a.
Purchasing and SCM (Larson & Halldorsson, 2002)

While contemporary supply chain literature (Tan et al., 1998; Gunasekaran & Ngai, 2005) have argued three key components of SCM (purchasing, quality management, and customer service), this dissertation follows Kraljic (1983) and relabels the “Purchasing” component to “Purchasing and supply management (PSM)” in an effort to encompass SCM within the realms

of a comprehensive approach to sourcing, operations, materials, and logistics management. We thus propose a view, both in line with the unionist (in that SCM subsumes purchasing) as well as with the intersectionist (in that SCM coordinates cross-functionality across purchasing, quality management, and customer service), where SCM subsumes PSM, and PSM in turn subsumes value sourcing. This is shown in Figure 1b.



SSCM: Strategic Supply Chain Management

QM: Quality Management

CS: Customer Service

VS: Value Sourcing

PSM: Purchasing and Supply Management

FIGURE 1b.
Value Sourcing, Purchasing and SCM

As supply chains spread globally, the impact on sourcing is significant. Today, sourcing is “an advanced approach to supply management that involves integrating and coordinating common materials, processes, designs, technologies and suppliers across worldwide buying, design and operating locations” (Trent & Monczka, 2005), thereby emphasizing organizational competitiveness by shifting from a mindset of narrow cost-reduction emphasis to one of globally integrated and coordinated strategy. An efficient value sourcing strategy thus acts as the liaison between the supply base and customer requirements by building on three necessities: to closely align buying cycles with production requirements (due to new manufacturing and IT trends), to

streamline purchasing and supply management activities for cost containment and elimination of “non-value added” tasks, and to facilitate the general trend towards outsourcing and increased reliance on suppliers for critical materials and components (Kocabasoglu & Suresh, 2006).

1.3. Research Objectives

The objectives of this research are as follows:

- a. Understand the continued shift of supply chains to value chains and justify the inclusion of “environmental sustainability” as a core attribute of value chains, given the growing concerns over global warming and carbon footprints.
- b. Investigate sourcing activities that facilitate value in a supply chain by mapping these sourcing activities to the well documented competitive priorities, i.e., speed, cost, quality, and reliability (Fine & Hax, 1985; Lee, 2004; Ketchen & Hult, 2007) as well as to the attributes of a value chain, i.e., agility, adaptability, alignment (Ketchen et al., 2008), and environmental sustainability.
- c. Conceptualize a framework for value sourcing by creating a logical sequence of sourcing activities which connects input measures (value chain attributes) to the competitive priorities, thereby following a managerial decision making process that builds on two core tenets: one, converting performance metrics to cost, and two, analyzing costs to make sourcing decisions that contribute to the value chain.
- d. Illustrate the *realization of costs from performance metrics* using a mathematical optimization model that quantifies supplier delivery performance into cost and enhances responsiveness in the supply chain by minimizing this cost function.

- e. Illustrate *decision making using cost analysis* by optimizing the buyer spending for continuous improvement of delivery performance towards understanding supplier capabilities as well as supplier management.

1.4. Organization of the Dissertation

In light of the research objectives stated in Section 1.3, we introduce a “value sourcing” framework with a supporting set of quantitative models. This dissertation, in the form of three essays, provides a recipe for establishing responsive supply chains in today’s competitive business landscape and contributes to meeting the challenges of managing suppliers in a global supply chain.

The *first* essay establishes a conceptual framework for value sourcing. We frame our design of the value sourcing framework in two phases; phase I emphasizes the relationship between supplier performance and cost, where supplier performance drives supplier evaluation. Phase II emphasizes the relationship between cost and sourcing decision making, wherein supplier evaluation impacts the sourcing decision.

Building on Phase I of our conceptual framework from essay 1, the *second* essay designs a mathematical framework that links the value sourcing initiative of supplier evaluation to a supplier’s delivery performance. We minimize the costs associated with untimely delivery and investment to improve delivery performance and present a model to enhance buyer-supplier alignment in the supply chain. Finally, building on Phase II of our conceptual framework from essay 1, the *third* essay uses an optimization model to link costs of penalty and improvement to supplier selection and management, the decision outcomes of value sourcing. In this final essay,

guided by a prescribed budget constraint for continuous improvement, we optimize the buyer spending for improvement in supplier delivery performance to gauge supplier capability as well as supplier management.

This research contributes to both academia and practice. First, the value sourcing framework addressed in the first essay maps supplier performance to buyer cost, thereby supporting supplier evaluation and selection. In mapping cost to decision making, the framework also addresses supplier development. In the second essay, an optimized penalty cost model for untimely delivery quantifies supplier delivery performance in metrics (probability and cost), which is of importance to researchers and practitioners alike. Third, the optimization model in the third essay not only illustrates containment of buyer spending for improvement due to optimum supplier capability, but also uses the buyer spending function to address supplier management under a constrained budget for continuous improvement.

The rest of this dissertation is arranged as follows. Chapter 2 (the first essay) presents a conceptual framework for value sourcing. Chapter 3 (the second essay) presents a penalty cost model for untimely delivery to illustrate the relationship between performance metrics and cost. Chapter 4 (the third essay) presents an optimization model for buyer spending on improvement that contributes to understanding supplier capabilities for subsequent supplier selection as well as to supplier management within a constrained budget for improvement, therefore illustrating the relationship between cost analysis and managerial decision making. Finally, Chapter 5 summarizes supply chain perspectives on value sourcing in general and delivery performance in particular, and concludes with directions for future research.

CHAPTER 2 (Essay # 1)

A CONCEPTUAL FRAMEWORK FOR “VALUE SOURCING”

2.1. Introduction to Value Sourcing

In his seminal work on the implementation of competitive strategy to achieve superior business performance, Michael Porter (Porter, 1985) developed and popularized the concept of “value chain”, i.e., activities that work together to provide “value” to the end customer. In the context of supply chain management (SCM), a customer-focused corporate vision (Tan, 2001; Foster, 2008; Gunasekaran et al., 2008) is a key facilitating mechanism for incorporating customer value. Today, most corporate initiatives are aimed at providing value to customers with short delivery times and high service levels while simultaneously maintaining cost efficiencies. As an example, Dell Inc. banks on customer requirements to create a product curtailed specifically to the customer’s need. Dell’s adherence to customer value is echoed in the thoughts of its President and CEO, Michael Dell (available in Enterprise Networks and Servers February 2007 issue):

“...it is important that we increase our ability to manufacture close to our customer and fully integrate our supply chain into one global organization. This will allow us to drive for even greater excellence in quality, cycle time and delivered cost.”

With the growth of the internet and e-commerce, sensitivity of customers to timeliness, price, and quality has increased manifold. Thus Henry Ford’s epigram, “The customer can have any color as long as it is black” has today entered American Folklore and is best suited in Utopia. Shifts in customer expectations and increased global competition in an environment where resources are more and more geographically dispersed has increased complexity in supply chain linkages between organizations, therefore necessitating control and management of resources to

succeed in this emerging global economy (Bozarth et al., 1998; Miles & Snow, 2007). The evolution of SCM continues in the twenty-first century as organizations extend best practices in managing resources (Cheung et al., 2010).

Appeasing customer needs is a challenge that many firms fail to cope with. Creating a sourcing framework that facilitates responsive supply chains in today's competitive global landscape, thereby instilling value to the end customer, is one way of dealing with such challenges. As supply chains spread globally, risks of disruptions become less controllable and more costly. Since sourcing is often times viewed as the "inbound" portion of a supply chain (i.e. from raw material to manufacturer), its increasingly significant role in the supply of products and/or services amidst these risks cannot be underestimated (Gottfredson et al., 2005; Craighead et al., 2007; Bhattacharyya et al., 2010). We address this growing importance of sourcing activities in the value chain by introducing a conceptual framework for "value sourcing".

Building on the work of Lee (2004), Ketchen et al. (2008) developed the concept of best value supply chains, i.e. business chains where flow of supply complements the flow of value. This essay investigates the contribution of sourcing to best value supply chains. Given the growing concerns over global warming and carbon footprints that are forcing end-users to reconsider environmental sustainability in the usage of products and/or services (Linton et al., 2007), we extend the value chain attributes laid out by Ketchen et al. (2008) by introducing *environmental sustainability* as a core attribute of best value supply chains. We then identify sourcing initiatives, a set of buyer actions, which in conjunction with supplier performance, guides sourcing decisions to contribute value in the supply chain. We coin this set of sourcing initiatives as *value sourcing*, a prerequisite for establishing best value supply chains in today's competitive global landscape. Finally, we lay out a conceptual framework for value sourcing.

To date, most of the research into sourcing decision making has been based primarily on analytical modeling (Talluri & Narasimhan, 2004) and case/field study data (Steinle & Schiele, 2008). Given the potential importance of sourcing decisions in carrying value to the end customer, the major challenge now facing researchers is to conceptually establish a rigorous and sufficiently comprehensive customer-focused sourcing framework. Such a framework can be used to identify the critical dimensions of sourcing decision making; it can also be used to identify those sourcing decisions that are most appropriate for addressing specific customer requirements. While the choice of single vs. multiple sourcing, or the decision to enter a contractual agreement vs. partnering has been extensively discussed in the sourcing literature in the light of supply chain risk, product positioning, and supplier capacity (Burke et al., 2007; Costantino & Pellegrino, 2010), a conceptual framework that illustrates the choice and prioritization of sourcing initiatives that lead to these decisions by mapping sourcing initiatives to customer requirements is largely missing. This essay contributes to this gap in the literature by developing a conceptual framework for value sourcing that can be used for both supplier evaluation (a key sourcing initiative) as well as supplier selection (a sourcing decision).

This essay further contributes to the literature in that it elucidates the importance of sourcing initiatives to customer-driven value chains by integrating sourcing activities to the overall scheme of best value supply chains. The impact of sourcing decisions and their contribution to value in the supply chain is explored in detail in our framework by mapping sourcing initiatives to value chain attributes. Based on a comprehensive review of the sourcing literature, we identify six sourcing initiatives (Table 1) that describe and assess our sourcing framework and its underlying design. More specifically, our value sourcing framework focuses on how value can be translated from these sourcing initiatives to the supply chain.

Sourcing Initiatives	Brief Description	Related Supply Chain Literature
Assessing Supply Risk	As supply chains spread globally, risks of operational disruptions become less controllable and more costly. Supply Chain Risk Management has grown into an independent research area in the recent past. Supply risk, as moderator of supplier performance, enables the buyer to make better cost decisions.	Narasimhan and Talluri (2009) Braunscheidel and Suresh (2009) Chopra and Sodhi (2004) Zsidisin (2003a, 2003b) March and Shapira (1987)
Early Supplier Involvement	Early supplier involvement involves supplier participation at concept or design/redesign phase of product development, thus taking advantage of supplier design capabilities.	Song and Di Benedetto (2008) Humphreys et al. ((2007) Zsidisin and Smith (2005) Hallikas et al. (2004) O'Neil (1993)
Green Procurement	Green Procurement is the philosophy of procuring and supporting the design of physical objects and/or services that comply with the core principles of economical, social, and ecological sustainability.	Pagell et al. (2010) Walker et al. (2008) Chien and Shih (2007) Linton et al. (2007) Sarkis (2003)
Supplier Evaluation	This is done by capturing the cost incurred to the buyer for sourcing a product; aids buyers by considering all costs associated with sourcing an item, which includes the supplier's manufacturing cost, added penalty costs of quality and lead time, and the cost of supply risks.	Ankarani (2009) Sarkar and Mohapatra (2006) Talluri and Narasimhan (2004) Ferrin and Plank (2002) Degraeve et al. (2000)
Supplier Development	Supplier development becomes essential when a supplier is not up to speed with the buyer's expectations, yet has potential to perform upon guidance and/or switching costs are high. When facilitated, supplier improvement and success lead to better long-term benefits to both parties.	Ghijsen et al. (2010) Modi and Mabert (2007) Dunn and Young (2004) Krause et al. (1998) Krause and Ellram (1997)
Trust	Trust is the degree of rational cooperation that needs to exist between two parties to make a relationship functional. Increase in trust helps mitigate market inefficiencies.	Cai and Yang (2008) Huang et al. (2008) Terpend et al. (2008) Johnston et al. (2004) Sako and Helper (1998)

TABLE 1
Value Sourcing Initiatives

Our value sourcing framework follows the two essential tenets of managerial decision making: using performance measures to realize costs, and subsequently using cost analysis to make informed and rational business decisions. The framework also adds to the existing literature in supplier evaluation by addressing supplier development in conjunction with supplier selection and evaluation, therefore integrating continuous improvement to both theory and practice.

The remainder of this essay is organized as follows: Section 2.2 expands on the best value supply chain concept as it has been reported in literature to date. Section 2.3 presents the conceptual framework. Finally, Section 2.4 discusses how our value sourcing framework offers new insights on the integration of value analysis with supply chain management, and concludes by addressing implications of this framework to both theory and practice.

2.2. Best Value Supply Chains: A Critical Analysis

2.2.1. Best Value Supply Chains and Environmental Sustainability: The Missing Link

In a Harvard Business Review article, Lee (2004), based on his extensive research on more than sixty companies, concluded that top performing supply chains possess three distinct qualities: *agility*, i.e., the ability to respond speedily to sudden changes in demand and/or supply; *adaptability*, i.e., the ability to adapt over time as market structures and strategies evolve; and *alignment*, i.e., the ability to create a synergy in the interests of all firms in the supply network to optimize the performance of the supply chain. Building on this “Triple-A Supply Chain” concept of Lee, and following the value chain concept of Porter (1985), Ketchen and Hult (2007) structure “best value supply chains” based on value to the customer imparted by the competitive

priorities speed, cost, quality, and reliability that render an agile, adaptive, and aligned business environment (Table 2).

The Case for Value	Best Value Supply Chains
Competitive Priorities	Total value across speed, quality, cost, and reliability
Agility	Strong ability to be proactive as well as responsive to changes
Adaptability	Maintain a limited set of multiple chains to ensure distribution
Alignment	Interests of participants coincide

TABLE 2
Attributes of Best Value Supply Chains (Ketchen & Hult, 2007)

Based on traditional perceptions of customer satisfaction and “total value” to a customer, an agile, adaptive and aligned supply chain that caters to speed, quality, cost, and flexibility has been well accepted in both academia and practice. However, in the past decade, owing to the spread of industrialization in all parts of the globe, third-world countries like China, India, and Brasil have emerged as the superpowers of tomorrow. With their abundant supply of manpower, technical expertise, and low labor costs, these developing countries have taken global competitiveness to a different level. With consumer spending increasing, consumption of energy and natural resources in these countries has catapulted beyond boundaries. Wall Street Journal’s report in the summer of 2010 that China, for the first time, has topped the chart in energy use ahead of the United States (Swartz & Shai, 2010) thus comes as no surprise.

As industrialization and technological innovations increase, widespread usage of natural resources continues to grow. With the global industrial revolution in full swing, biodiversity losses continue, leading to huge repair costs that companies end up paying for the deteriorating or vanishing ecosystems (Srivastava, 2007; Beamon, 2008). Gradual depletion of the ozone layer is no longer a myth (Goldey et al., 2010). The recent oil spill off the Gulf of Mexico is a case in point. In the aftermath of the gulf oil spill, the (now) infamous snapshots of pelicans covered in oil from ruptured undersea oil-wells has made the human race pause and take notice of its increased and continued support to ecological imbalance (Slatin et al., 2010). This is where environmental sustainability can play its role to avert ecological problems and help in not only building a better image of industrious companies, but also rendering them sustainable in the long run. In short, the current imbalance in nature calls for an increased need for firms to behave as responsible environmental citizens, making it timely and appropriate (Barry, 2006) for “environmental sustainability” to find its place within the structuration of best value supply chains.

2.2.2. Value in Environmental Sustainability

The case for environmental sustainability in a supply chain’s competitiveness and the role of purchasing therein has been well documented (Linton et al., 2007; Krause et al., 2009). We re-emphasize the point that value is what the end-customer in a supply chain perceives to be. Therefore, in order that environmental sustainability is considered an attribute for value chains, it is imperative that customers see value in environmental sustainability. Given that value in a product is a function of its increased usage/awareness, growing awareness towards environmental-friendly-living has driven customers towards greener products; examples abound: hybrid cars, solar panels for power, and biodegradable cleaning products, among others. This

growth in customer awareness for green has been reflected recently in both academia and practice. A survey by Linton et al. (2007, p. 1077) shows that research articles pertaining to the concept of sustainability in the management literature have increased in frequency from 3 out of 1000 in the year 1990 to 15 out of 1000 in the year 2005. On the same token, a 2010 article in the Wall Street Journal on the availability of Seventh Generation biodegradable detergent products at the shelves of Wal-Mart states that “sales of green household and laundry cleaning products rose to \$557 million in the year 2009, having more than tripled since 2005, according to estimates from market research firm Packaged Facts” (Byron, 2010), echoing value in environmental sustainability.

While establishing value in environmental sustainability, we concede that inculcating any set of values within a firm is far easier than permeating the same set of values through the entire supply chain. In this context, it needs to be realized that the appreciation for “going green” in the customer’s mindset is a prerequisite for this entire flow of value via sustainability measures adapted by members of the supply chain. In growing awareness of the environment around us, we contend that a firm delivering green products and/or services to a customer helps increase value in the mind of the customer. Figure 2 illustrates the flow of products and/or services in a supply chain as a result of the opposite flow of product/service expectations, driven by the perceived value of an end-customer in green.

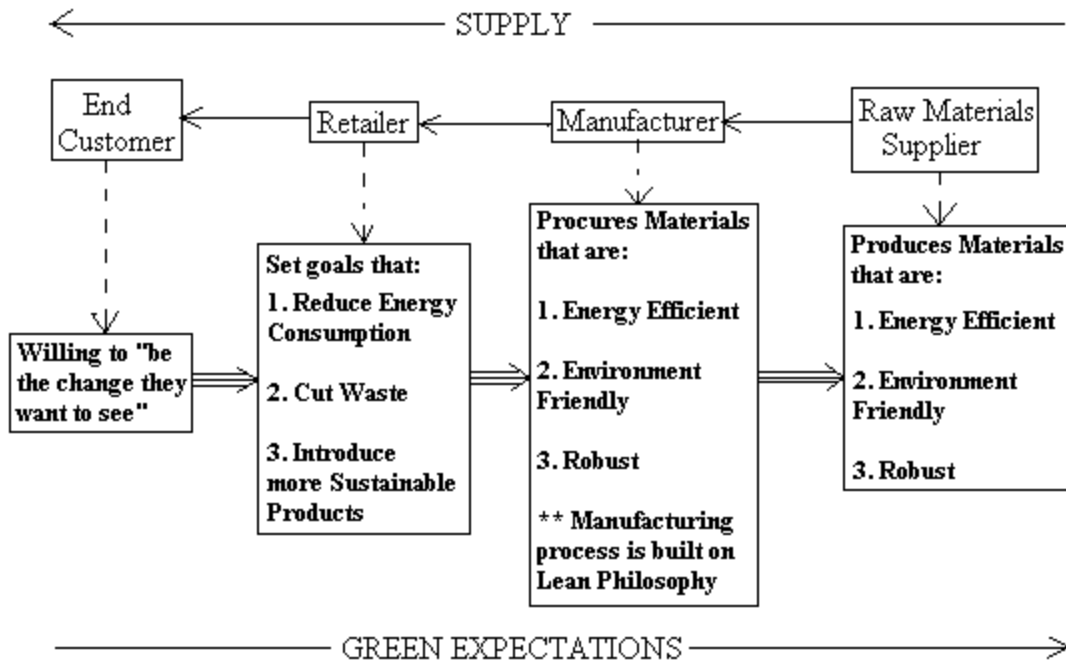


FIGURE 2
Value propagation in the Supply Chain due to Green

The following case of Wal-Mart reflects the responsibilities and actions of a model retailer to promote environmental sustainability in a supply chain, as illustrated by Figure 2. For Wal-Mart, famous for competing on price and volume, considerations towards higher-priced “green” options were a distant priority until a few years back. However, the growing propensity of customers towards environment-friendly products made Wal-Mart think otherwise. Today, Wal-Mart has taken steps towards *reducing energy consumption* by a variety of means that include (i) reducing energy use at its more than 7000 stores worldwide by 30%, (ii) taking initiatives to reduce green house gas emissions by 20% through 2013, and (iii) replacing gasoline driven trucks by hybrid trucks towards greener transportation, among others. In an effort to *introduce more sustainable products*, Wal-Mart has ensured that 100% of wild salmon sold in Wal-Mart stores are from fisheries certified by the Marine Stewardship Council, an independent body for

sea-life conservation (Byron, 2010). Based on recent customer awareness towards greener environments, we extend the value attributes of a supply chain, i.e., agility, adaptability, and alignment (Lee, 2004; Ketchen & Hult, 2007) to a fourth dimension: environmental sustainability. The next section discusses how sourcing activities contribute to these value attributes.

2.3. Towards a Conceptual Framework for Value Sourcing

The thrust of this essay is to understand how sourcing activities facilitate the success of best value supply chains by balancing the four attributes of value, i.e., agility, adaptability, alignment, and environmental sustainability to achieve one or more of the competitive priorities, i.e., speed, quality, cost, and flexibility. The foundation of our conceptual framework for value sourcing is based on the six sourcing initiatives (identified in Table 1) that buyers use in supplier selection and management. The following sub-sections discuss the scope and use of conceptual frameworks in the operations management (OM) and/or supply chain management (SCM) literature, describing the distinguishing characteristics that form a conceptual framework, therefore validating the framework used in this essay.

2.3.1. Scope and Use of Conceptual Frameworks in OM/SCM Literature

Conceptual frameworks in supply chain management literature, especially papers that have investigated factors leading to supply chain responsiveness towards customer requirements, while differing considerably in their forms (Schmenner, 2009), can be clustered into five common types (Holweg & van Donk, 2009) – descriptive mind maps, relational frameworks, causal frameworks, venn-diagrams, and narrative frameworks.

Descriptive mind maps lay out the main factors or constructs in a certain field of interest and show a connection between them, but without causality or directionality. Within this framework variables may be shown in a hierarchy of different levels of aggregation (Koste & Malhotra, 1999, p87). Adding a further level of restrictions, *relational frameworks* highlight the main variables of interest, alongside the connections between these variables. Connections are generally unidirectional, but may also be bi-directional to depict mutual influence. A special case here is the *causal framework* where connections direct into one way to imply causality. In the latter case the model, due to incorporation of “causation”, distinguishes between dependent and independent concepts, constructs, or variables (Frohlich & Westbrook, 2002, p733). Thirdly, *Venn diagrams* (or *set diagrams*) show all hypothetically possible, logical relations between a set of entities. The aim of this type of framework is to show all entities at the same level, in one space, where each entity can be associated with a specific set or attributes of entities. Finally, *narrative frameworks* that can be based on any of the above forms verbally express what the above show in a graphical form.

The conceptual framework created in this essay is essentially a descriptive mind map composed of six sourcing initiatives (Table 1) leading to three sourcing outcomes: single vs. multiple sourcing, contracting vs. partnering, and supplier selection. We thus distinguish the role of sourcing initiatives from sourcing outcomes within the elements of our framework. The purpose of this framework is to summarize the main concepts, constructs, and elements of value sourcing in a logical, structured, and hierarchical way to depict how value sourcing balances the four attributes of value, i.e., agility, adaptability, alignment, and environmental sustainability to achieve one or more of the competitive priorities, i.e., speed, quality, cost, and flexibility. The hierarchy of our framework in terms of the value sourcing initiatives and their position between

supplier performance and the three sourcing outcomes is illustrated in the tiered hierarchical structure in Figure 3.

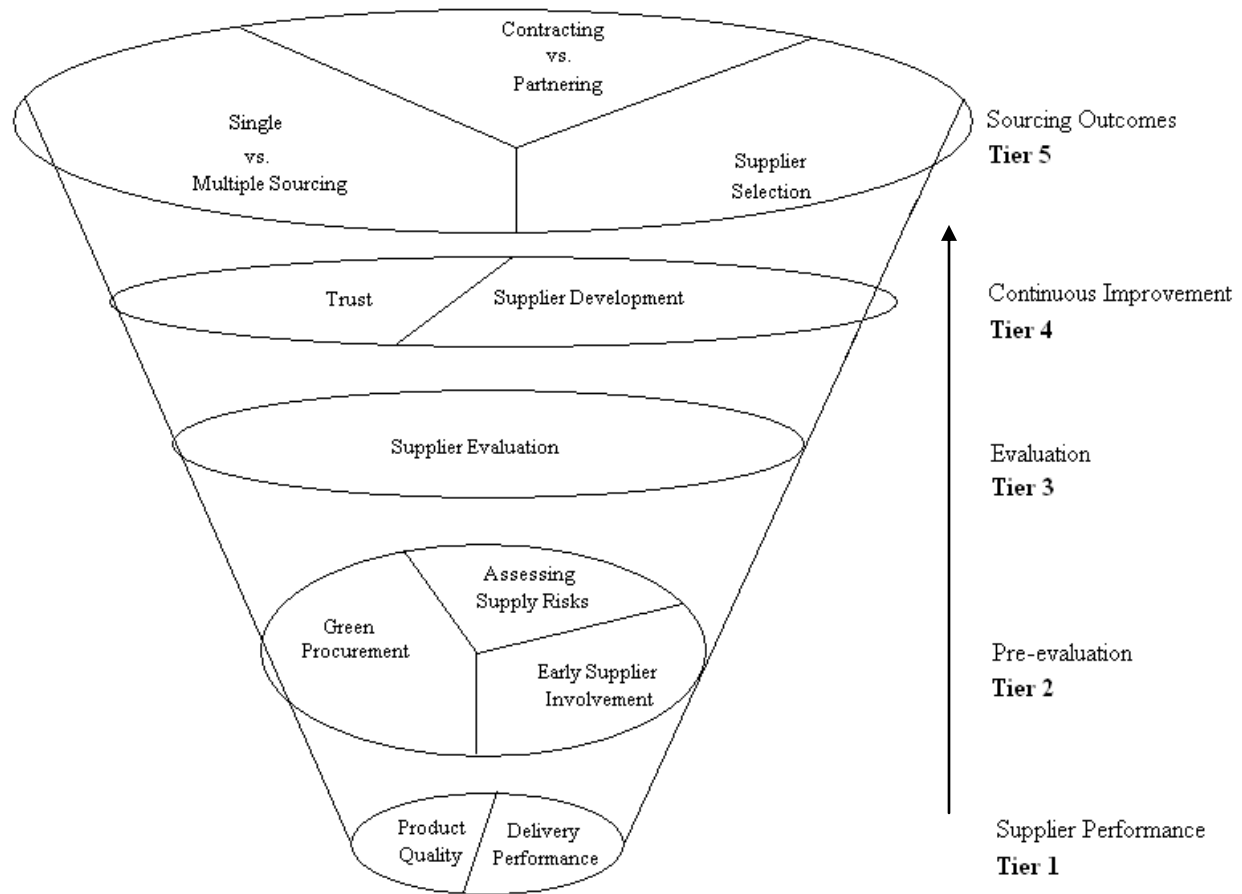


FIGURE 3
Hierarchy of Value Sourcing Framework Components

We design our value sourcing framework in two distinct phases that follow a logical sequence towards the basic managerial decision-making process. The *first* phase emphasizes the relationship between supplier performance and buyer cost, where supplier performance drives supplier evaluation. The *second* phase emphasizes the relationship between buyer cost and sourcing decision making, wherein supplier evaluation leads to sourcing outcomes. Our framework seeks to explain the structuration of the sourcing activities and the relationship of the

sourcing activities to the four inputs (value chain attributes) as well as to the four outputs (the competitive priorities¹) as drawn in Figure 4.

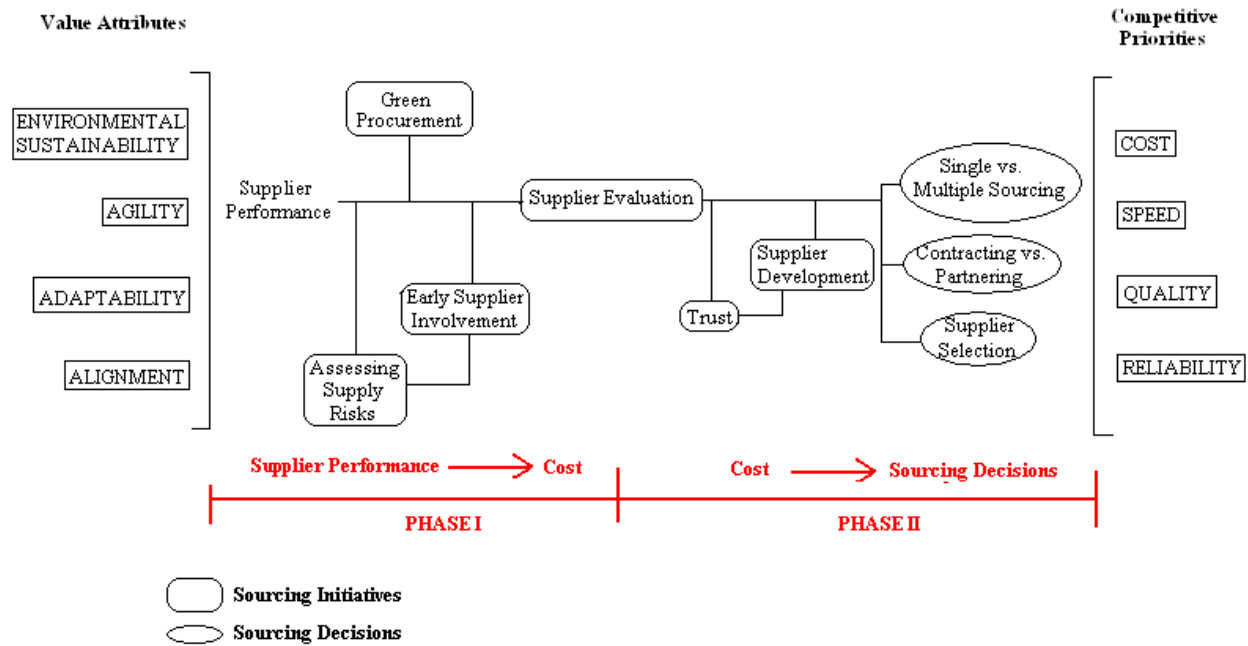


FIGURE 4
A Conceptual Framework for Value Sourcing

In the following subsections, we elaborate on phases I and II by drawing key propositions that map value sourcing initiatives to the attributes of best value supply chains as well as to competitive priorities.

2.3.2. Phase I: Supplier performance to cost realization

Supplier performance is attributed to supplier delivery and product quality. In a volatile global business environment, supply risks influence supplier performance, and the impact of supply risk on supplier performance is perceived by the buyer to the extent a supply scenario is deemed “risky” by the buyer. A sourcing framework to understand supplier performance needs

¹ The competitive priorities Speed, Cost, Quality, and Reliability as shown in Figure 4 do not necessarily have to

to consider the impact of supply risk on competitive priorities - speed, cost, quality, and reliability, which in turn is governed by the buyer's perception and assessment of risk. This assessment of supply risk is grained into the buyer's evaluation of the supplier, as is the buyer's decision to procure environmentally sustainable products. The latter, while alleviating overall cost to the buyer in the short run renders a cleaner environment, eventually making the buyer a responsible corporate citizen.

Assessing supply risks. As supply chains spread globally, risks of operational disruptions become less controllable and more costly. Supply risks abound: the recent earthquakes in Japan leading to radioactive leakage, maritime attacks in the Gulf of Aden, H1N1 in Mexico, SARS in Hong Kong, currency crisis and supplier insolvency in Argentina, credit meltdown in Iceland (Bhattacharyya et al., 2010). Assessing supply risk is thus an area of paramount importance in sourcing. Supply risk is perceived to exist when there is a relatively high likelihood that a detrimental event can occur and that event has a significant associated impact or cost (March & Shapira, 1987; Shapira, 1995; Hallikas et al., 2004; Zsidisin et al., 2004). The likelihood and impact of a detrimental event may hamper speed, quality, cost, or reliability.

Supply risks reduce speed, quality, and reliability in a supply chain, while increasing costs. As an example, in June of 2009, two days after the H1N1 was defined as a pandemic by the World Health Organization (WHO), the US closed all land routes to and from Mexico (Shah, 2009). Mexico lost \$57 million per day from operational threats related to the H1N1 virus. This example is an instantiation of the impact of risk on speed of delivery and related spikes in cost. Lower speed in the supply chain increases lead time, which in turn reduces reliability. Thus, as supply risks impact speed, cost, and reliability, it is imperative that such risks be assessed in the realization of costs from supplier performance. Mitigating risks through sourcing activities also

builds supply chain agility (Braunscheidel & Suresh, 2009; Narasimhan & Talluri, 2009).

Therefore we propose:

Proposition 1: A sourcing initiative towards assessing supply risks leading to supply chain agility may achieve the expected levels of speed, cost, and reliability in the supply chain, thereby instilling value.

Early supplier involvement. Another important sourcing initiative that enhances supplier evaluation is early supplier involvement. Early supplier involvement involves supplier participation at concept or design/redesign phase of product development, thus taking advantage of supplier design capabilities (O'Neal, 1993). Recent literature on supply chain risk has profusely cited early supplier involvement to mitigate risks and enhance buyer-supplier relationships (Chopra & Sodhi, 2004; Hallikas et al., 2004). In reality, supply chains practicing early supplier involvement have been found to achieve significant reductions in material cost and development time, while improving material quality (Monczka et al., 2009). In terms of adding value, early supplier involvement increases the length of relationship between the buyer and supplier and enforces common interest between the two parties, therefore paving the way to operational synergy and hence, alignment. Therefore, we propose:

Proposition 2: A sourcing initiative towards early supplier development leading to supply chain alignment may achieve the expected levels of speed, cost, quality, and reliability in the supply chain, thereby instilling value.

Green procurement. A core sourcing initiative that arises out of our earlier discussion of environmental sustainability is green procurement. *Green* or *Sustainable Procurement* is a sourcing initiative that can lead to environmental sustainability (Pagell et al., 2010). Green

Procurement is the philosophy of procuring and supporting the design of physical objects and/or services that comply with the core principles of economical, social, and ecological sustainability (Sarkis, 2003). Recyclable and environmentally friendly packaging materials, optimized travel routes and use of hybrid-powered vehicles to reduce transportation-related carbon footprint, green focus in corporate strategy, and energy conservation are key to environmental sustainability. Green procurement can be enforced into our value sourcing framework by incorporating a *sustainable procurement checklist* for suppliers that include the following considerations:

- avoid ozone depleting chemicals in mechanical equipment and insulation (i.e. CFC vs. HCFC)
- use durable materials that last longer and require less maintenance
- choose building materials with low maintenance and low embodied energy
- optimize travel routes and use hybrid-powered vehicles to reduce transportation-related carbon footprint
- minimize packaging waste

As the above discussion suggests, the inclusion of environmental sustainability as an attribute of value chains also introduces a potential paradox: traditionally, environmentally friendly endeavors have not proven to be cost effective in the short run (as an example: the fixed costs of alternative sources of energy like biomass, fuel cells, solar, nuclear, etc. are much higher than the traditional sources), whereas agility, adaptability, and alignment are all antecedents to low cost. Therefore, incorporating “green” within the schema of best value supply chains, we propose:

Proposition 3: A sourcing initiative towards green procurement may require *re-balancing* the value attributes – agility, adaptability, alignment, and environmental sustainability

along the lines of expected levels of speed, cost, quality, and reliability in the supply chain, thereby instilling value.

Supplier evaluation. A formidable advantage of best value supply chains lay in the traceability of total supply chain performance by gaining insights into total value across speed, cost, quality, and flexibility. In the sourcing world this translates to evaluating the performance of suppliers from which the product and/or service is sourced. An important aspect of sourcing remains the realization of cost to the buyer due to supplier performance. Realization of cost from supplier performance leads to *supplier evaluation*, which aids buyers by considering all costs associated with sourcing an item from the supplier. Numerous quantitative models have been developed for evaluating supplier performance and have been reported in the purchasing, logistics, and operations management literature (Guiffrida, 1999; Degraeve et al., 2000). Talluri and Narasimhan (2004, p. 239) provide a comprehensive list of supplier evaluation techniques used till date. In essence, all these techniques aim at reducing total cost to the buyer, which includes (but is not restricted to) the supplier's manufacturing cost, added penalty costs of quality and delivery, and the cost of supply risks (Ferrin & Plank, 2002).

Supplier evaluation is also necessary to gauge alignment of interest between the supplier and buyer (Ancarani, 2009), which eventually translates to overall supply chain alignment. An essential total quality management (TQM) tool for buyers, supplier evaluation not only evaluates supplier performance and the associated cost to the buyer, but also requires suppliers to initiate statistical process controls (SPC), design of experiments (DoE), process capability studies, etc. to help the buyer better gauge supplier capabilities (Sarkar & Mohapatra, 2006). We propose:

Proposition 4: A sourcing initiative towards supplier evaluation leading to agility, adaptability, alignment, and environmental sustainability may achieve the expected levels of speed, cost, quality, and reliability in the supply chain, thereby instilling value.

2.3.3. Phase II: Decision Making from Cost Analysis

A comprehensive approach towards supplier evaluation and sourcing initiatives towards supplier development and trust, can help answer questions pertaining to (i) the decision of single vs. multiple sourcing, (ii) the decision of contracting vs. partnering, and (iii) supplier selection. The following subsections will reveal that a (portfolio of) supplier(s) selected following the framework presented herein is poised to balance all four attributes of value sourcing, namely agility, adaptability, alignment, and environmental sustainability to cater to the competitive priorities.

Supplier development. Only when a supplier is monitored and evaluated is supplier development possible. Supplier development becomes essential when a supplier is not up to speed with the buyer's expectations, yet has potential to perform upon guidance and/or when switching costs are high (Krause, 1997). When the buyer facilitates supplier improvement, supplier improvement and success in turn leads to better long-term benefits to both parties (Watts & Hahn, 1993; Krause & Ellram, 1997). Long-term interaction between the buyer and the supplier not only works towards building mutual trust (Humphreys et al., 2004), but also facilitates towards better alignment and commonality in mutual interests (Modi & Mabert, 2007). We propose:

Proposition 5: A sourcing initiative towards supplier development leading to agility, adaptability, alignment, and environmental sustainability may achieve the

expected levels of speed, cost, quality, and reliability in the supply chain, thereby instilling value.

Trust. Trust is the degree of rational cooperation that needs to exist between two parties to make a relationship functional (Huang et al., 2008). Trust in this context is essentially dyadic, between the buyer and supplier and is perceived from the lens of a buyer. The buyer's trust in the supplier significantly affects the decision of single vs. multiple sourcing, or the decision of contracting vs. partnering. For example, buyers are constantly torn between the decisions to build lasting relationships with suppliers for business continuity in trying times, thereby putting complete trust on one supplier, versus the need to build redundancies in the supply chain with multiple sourcing alternatives to hedge against the risk of supply from a single supplier.

The following example with Motorola helps understand adaptability from the context of trust with single vs. multiple sourcing. Motorola Inc. buys many of its handset components from multiple vendors. Doing so prepares the company for disruptions without building up fast-depreciating inventory. Motorola lowers the cost of redundancy by using multiple suppliers for high-volume products and single sourcing for low-volume products. If disruptions in the supply chain increase, Motorola will accordingly assess supply risks and increase its dependence on multiple vendors, instead of its trust in any single one.

Trust is a critical aspect of buyer-supplier relationship that leads to operational synergy (Terpend et al., 2008). Operational synergy in buyers and suppliers refers to the strength in alignment of their respective belief, culture, core competencies, etc. to facilitate operational excellence. Buyers face two strategic decisions when engaging in a new purchase transaction: the decision whether to draft a detailed contract and the decision whether to select a supplier with

which they share an established relationship. The buyer's trust on the supplier influences these decisions and the effectiveness of these decisions in curtailing the supplier's opportunistic behavior in different ways (Williamson, 2008). Selecting a supplier with an existing relationship shows a marked ability to hedge against supplier opportunism, but beyond a certain point, *it encourages the opportunism it is designed to discourage* (Wuyts & Geyskens, 2005).

Contracting tends to become more effective when a less reliable supplier is selected and when the focal relationship is embedded in a network of close mutual contacts. Often times, a good working relationship over time increases mutual trust and replaces a detailed contract by an informal partnering agreement, characterized by a mutual commitment to problem solving and cost reduction (Mohr & Spekman, 1994; Bozarth et al., 1998; Cai & Yang, 2008). We thus propose:

Proposition 6: Between short term 'multiple sourcing' and long-term 'relationship building' approaches, trust varies in different degrees to enhance alignment between the buyer and supplier while still maintaining the ability to adapt and respond to a sudden change.

Table 3 summarizes the attributes of best value supply chains and the sourcing initiatives that facilitate best value supply chains. To the best of our knowledge, this is the first attempt to map sourcing initiatives to value attributes of a supply chain.

The Case for Value	Sourcing Initiatives	Best Value Supply Chains
Agility	<ul style="list-style-type: none"> - Assessing Supply Risks - Early Supplier Involvement - Supplier Evaluation - Supplier Development - Trust 	Strong ability to be proactive as well as responsive to changes
Adaptability	<ul style="list-style-type: none"> - Early Supplier Involvement - Supplier Evaluation - Supplier Development - Trust 	Maintain a limited set of multiple chains to ensure distribution
Alignment	<ul style="list-style-type: none"> - Early Supplier Involvement - Supplier Development - Trust 	Interests of participants coincide
Environmental Sustainability	<ul style="list-style-type: none"> - Green Procurement 	A sustainable supply chain that is robust enough to support itself and improve the environment.

TABLE 3
Sourcing Initiatives for “Value”: A Case for *Value Sourcing*

2.3.4. Structural Validity of our Value Sourcing Framework

Historically, conceptual frameworks found in the supply chain literature have differed significantly in form, variables, and relationships considered, such that each author could logically “defend” or “justify” their respective frameworks. Yet despite considerable disagreement between them, there seemed no obvious reason to either prove or disprove any of them. Holweg and van Donk (2009) attribute this mess to a lack of guidance on how to build such frameworks in the first place. Miles and Huberman (1994) implicitly give a number of hints related to the quality of a framework, while Pfeffer (1982), Whetten (1989), and Handfield and Melnyk (1998) offer more explicit criteria. Based on these collective guidance, our conceptual

framework builds on the following four nuances that can be seen as “established criteria for good conceptual frameworks” and may be used as a model for future researchers using conceptual frameworks in the OM and/or SCM literature:

Selectivity and parsimony. Selectivity refers to a clear and logical justification as to why a conceptual framework includes the elements of the framework (Whetten, 1989). Parsimony refers to restricting the framework to the ‘vital few’ (Pfeffer, 1982). The rationale behind the choice of six sourcing initiatives in this essay towards value in a supply chain has been well established in the earlier subsections. We make the distinction between *sourcing initiatives* that define value, and *sourcing decisions*, the outcomes of these initiatives, which feed into other supply chain activities. Together, the set of initiatives and the decisions form the sourcing activities.

Comprehensiveness. Comprehensiveness refers to the involvement of the elements in the framework, given the intention of the framework (Whetten, 1989). While there is abundance in modeling techniques as far as supplier evaluation and supplier selection are concerned (Talluri & Narasimhan, 2004), the availability of a framework that addresses supplier development in conjunction with supplier selection and evaluation, is scarce. As an example, Krause et al. (1998) address strategies pertaining to only supplier development. This value sourcing framework, in mapping supplier performance to buyer cost, and cost to decision making, not only shows potential for supplier evaluation and selection but also addresses supplier development, therefore paving the way towards better buyer-supplier alignment and long-term buyer-supplier relationships leading to enhanced supply chain agility and adaptability.

Novelty. The novelty of a framework lies in the ability to have a conjecture into offering new insights (Siggelkow, 2007). Our value sourcing framework offers new insights in different ways. First, this essay extends the literature on value attributes in a supply chain (Lee, 2004; Ketchen & Hult, 2007; Ketchen et al., 2008) by integrating *environmental sustainability* into the value attribute set. Concepts pertaining to sustainability have increasingly found home to management literature, with an unprecedented increase in publishing frequency in the past decade (Linton et al., 2007). In line with this trend, our value sourcing framework advocates the inclusion of environmental sustainability into the structure of a value chain. Second, by including environmental sustainability as a value attribute for supply chains, our conceptual framework raises an interesting scope for future research as has been explained in “Discussion and Conclusions”. Third, while we structure the essay as a descriptive mind map for value sourcing, the research can be furthered towards empirical research by modeling causal frameworks.

Meaning. Meaning refers to the aid of the framework in helping understand existing, real-life managerial problems. The relevance to a practical problem seems to be the point of greatest agreement in the OM/SCM literature (Whetten, 1989; Schmenner, 2009). The following section discusses the implications of our conceptual framework to practice in detail.

2.4. Discussion and Conclusions

“You must be the change you wish to see in this world”

~ M. K. Gandhi

Careful analysis of “value sourcing” offers research opportunities in the study of supply chain performance metrics, single vs. multiple sourcing, and contracting vs. partnering. In a turbulent global trading environment, a comprehensive, customer-driven approach to supplier

evaluation demands judicious analysis of supplier performance coupled to the effects of supply risk. On the other hand, customer inclinations towards a greener environment calls for sourcing environmental sustainable products that may affect supplier performances if there is lack of alignment in sustainability interests between the buyer and supplier. We continue our discussion in this section by addressing the implications of this work to research and practice, followed by limitations of this framework and a summary conclusion.

2.4.1. Implications to Research

The conceptual framework for value sourcing presented in this essay enriches supply chain theory in multiple dimensions. While we structure the essay as a descriptive mind map for value sourcing, several avenues for future research open up by advancing this descriptive mind map to the next stage, i.e., a relational framework for value sourcing. We offer three potentially useful research avenues that may pivot on measuring the impact of value on competitive priorities.

First, propositions 1 through 6 drawn in the previous section (Section 2.3) need empirical testing. With single vs. multiple sourcing, and contracting vs. partnering being the prime sourcing decision areas that ultimately lead to supplier selection, empirical researchers can now model the right mix of value sourcing initiatives for a specific product/service that would lead to a partnering decision with a supplier, as opposed to a contractual agreement. Similar approaches can be empirically tested for single vs. multiple sourcing. Finally, a comprehensive analysis would advocate the correct mix of value sourcing initiatives in light of the number of suppliers being used (single vs. multiple sourcing) and the type of agreement (contractual vs. partnering) in providing a decision rubric in the hands of a practitioner.

Second, studies focused on empirically testing the nature of the hierarchical and lateral relationships between the four value attributes as proposed in this essay should be undertaken.

Within this context, researchers could seek to understand the nature of tradeoffs that may exist between the choices of value attributes. For example, are supply chains (or organizations within a supply chain) more likely to favor and promote one type of value attribute (e.g. agility) over the others? Is there synergy between some of the attributes? As an example, on face value, it seems that an adaptive and aligned supply chain is also agile. Further empirical testing will solidify the nature of relationship between these value attributes, whether they are strong, moderate, or weak. Finally, researchers and practitioners will gain from a comprehensive understanding of the degree of each of these value attributes the recipe for a sufficient building block towards attaining competitive priorities.

Third, the inclusion of environmental sustainability in the list of value attributes for best value supply chains creates an interesting mix. On the one hand, sustainable approaches to mitigate environmental hazards are often time and money consuming, with high starting costs; on the other hand, supply chains have traditionally looked at lean measures to account for agility through reducing costs. Adaptability and proper alignment further adds to agility. The question therefore is: to which end of this evaluation spectrum should a sourcing framework align itself to preserve the right balance of agility, adaptability, alignment, and environmental sustainability, yet maintain competitive advantage through speed, cost, quality, and reliability? As supply chains juggle between ‘short term’ cost containment using agile measures and ‘long-term’ cost containment using environmentally sustainable measures, sourcing initiatives move across a continuum in different degrees, begging an investigation on their role in optimizing supply chain performance. It would only be in the realm of conjecture to extrapolate from our framework and future research might find this study a stepping stone for seeking answers in the same genre.

2.4.2. *Implications to Practice*

Today's managerial decision-making seeks relevance to service and manufacturing businesses across the globe. This focus is most apparent in two areas (i) improving both process and systems operational performance across the supply chain and (ii) effectively using business analytics towards decision making in business organizations. In line with this practice, this essay proposes a value sourcing framework that essentially operates in two phases. The first phase of the framework dictates the conversion of performance measures to cost. The subsequent phase uses cost to drive sourcing decisions.

Second, we sketch a value sourcing framework that addresses supplier performance measures and maps performance to cost incurred by the buyer. Thus, the reason for fluctuations in the buyer's incurred cost can easily be attributed to a specific supplier performance measure, so that corrective actions can be taken. A buyer's allowable cost is typically constrained by the budget imposed on the buyer for that specific product. Thus, it is only in the realms of logic to understand supplier performance that best caters to buyer expectations within this defined ceiling.

Third, value at the customer's end is no longer constrained to cost alone, but the optimum blend of speed, cost, quality, and reliability that creates "the right experience" for the purchase. But here is the interesting twist: often times, it does not have to be *the one* 'right experience'. In other words, customers perceive their experience to be "right" in different ways based on their priorities. Thus the customer's priorities will lead to alignment of competitive priorities, which in turn will align the sourcing initiatives to provide maximum value to the customer. For example, Gap, Inc. uses a three-pronged strategy (Lee, 2004) to cater to its customer base through its three brands: Old Navy, Gap, and Banana Republic. It aims the Old Navy brand at cost-conscious

consumers. Thus, in terms of our value sourcing framework for Old Navy, cost will be at the top of the competitive priorities. Since green activities typically increase costs, we are more likely to see less of environmentally sustainable procurement in this regard. In reality, the entire manufacturing and sourcing for Old Navy is set in China to ensure cost efficiency, and China, in all its glory as a rising power, is yet to become an environmental sustainable nation. The Gap brand is designed for “trendy” buyers, and thus speed and reliability of delivery is of essence. To account for speed at the top of competitive priorities, our value sourcing framework would incorporate minimum supply risks and adherence to multiple suppliers in case of a disruption in supply. In fact, Gap maintains its chain in Central America to guarantee speed and reliability and minimizes supply routes to mitigate supply risks. Finally, the Banana Republic brand is aimed for customers who put quality ahead of everything. In this context, sustainable procurement may matter, as customers are willing to pay a premium for the excess quality. In spite of supply risks due to international logistics, Gap continues to maintain the supply network of Banana Republic in Italy to ensure quality. We thus contend that our value sourcing framework can help create these “set of experiences” for the end customer by adjusting sourcing activities in line with the competitive priorities, thereby creating “value” by balancing agility, adaptability, alignment, and environmental sustainability in the supply chain.

2.4.3. Limitations of the Framework

The conceptual framework addresses in this essay has a few limitations. *First*, the research is essentially viewed from the buyer’s lens. *Second*, although concurrent research has been conducted with multi-echelon supply chains, our scope for this framework remains a two stage supply chain which includes a buyer and a supplier, primarily for the sake of simplicity. The reason for this simplification is as follows: In a traditional supply chain the demand flows from

the end-customer to the raw materials producer via the retailer and the manufacturer. In essence, every pair in this supply chain can be qualified into a two-stage buyer-supplier scenario. Thus while on one hand, a manufacturer buys from its supplier, i.e., the raw materials producer; on the other hand, this same manufacturer is also a supplier to a retailer.

Third, our conceptual framework assumes initial screening of supplier capabilities via rapid plant assessments (RPA), etc., in place, i.e. supplier assurance in terms of the ability to meet quality and delivery requirements of the buyer and financial capabilities of the supplier are considered prior to entering the framework. *Lastly*, we also assume that the sourcing mechanism strictly remains between the buyer and the supplier. Often times, the buyer organization outsources part or the entire sourcing process to a third party logistics provider (3PL). Such complexities have not been captured in our framework.

2.4.4. *Summary Conclusion*

Renewed propensity towards customer-focus in today's volatile business environment has resurrected the importance of "value to the end customer" in supply chains. A supply management framework that balances performance and costs renders a supply chain effective and responsive, thereby instilling value. In light of growing environmental concerns over global warming and carbon footprints, this essay suggests the inclusion of environmental sustainability as a core attribute of best value supply chains and makes the case for a value sourcing framework that balances agility, adaptability, alignment, and environmental sustainability to provide speed, cost, quality, and flexibility to the supply chain. Guided by the impact of supplier performance and buyer strategies on supplier evaluation, and the subsequent utilization of supplier evaluation techniques in sourcing decisions and supplier selections, this essay formally defines value sourcing as *the process of procuring goods and/or services to meet the needs of the customer via*

a set of customer-focused supply management initiatives that enables an organization in the selection, development, and management of suppliers.

The next chapter (Chapter 3) optimizes a mathematical model for penalty cost that links the delivery performance of suppliers to cost realization for continuous improvement of supplier evaluation, a value sourcing initiative.

CHAPTER 3 (Essay # 2)

A PENALTY COST MODEL FOR UNTIMELY DELIVERY

Chapter 2 focused on how sourcing activities contribute to the design and implementation of sourcing strategies in adding value to the overall supply chain and laid out a conceptual framework for *value sourcing*. In this chapter, we develop a cost-based delivery performance model for untimely delivery to demonstrate *cost realization through performance measures* as illustrated in Phase I of our value sourcing framework (Figure 4).

3.1. The Importance of Modeling Delivery Performance

Over the past decade, there have been many instances where untimely delivery has led to increased costs and disruptions in global supply chains. For example, in the year 2000, late delivery of microchips from a Philips plant to Ericsson led to the latter's loss of \$400 million in sales (Chopra & Sodhi, 2004). In early 2006, the Chinese telecom giant, Huawei Technologies, estimated a fine of \$3 million per day to Thai authorities in the event of a failure to meet the deadline in providing CDMA base stations to Thailand by January, 2007 (Tortermvasana, 2006). And as recently as last year, Wal-Mart joined other retailers in imposing a penalty cost of 3% of the cost of the goods to suppliers failing to deliver products within Wal-Mart's prescribed four-day delivery window (Painter & Whalen, 2010). The aforementioned examples, while spanning a decade, echo a common theme: the cost of untimely delivery.

More than forty years back, Skinner (1969) led the renaissance of research on manufacturing strategy, incorporating the manufacturer's need for choosing among and achieving one or more key capabilities. In the 1980s, these key capabilities identified by Skinner reemerged in the operations management literature as "competitive priorities" (Hayes & Wheelwright, 1984;

Ward et al., 1998; Ketchen & Hult, 2007). In spite of minor semantic differences, there has been a broad agreement that these manufacturing competitive priorities can be expressed in terms of four basic components: cost, quality, speed and flexibility (Wheelwright, 1984; Fine & Hax, 1985; Ketchen et al., 2008). Recent research on theory building (Vickery, 1991; Wu & Pagell, 2010) and empirical research (Amoako-Gyampah & Acquaah, 2008) in manufacturing strategy continues to showcase the importance of these four basic capabilities. Timely delivery is core to supplier evaluation in that it not only addresses speed and reliability of the supplier but also costs associated with lack of timeliness that is incurred to the buyer.

In line with the established competitive priorities of speed, cost, quality and reliability, delivery performance of a supplier is a metric that is common to many supplier evaluation models. The importance of delivery performance as an attribute for evaluating supplier performance was recognized over forty years ago by Dickson (1966). Delivery performance continues to be consistently reported as a key metric in supplier evaluation models (Weber et al., 1991; Guiffrida, 1999; Degraeve et al., 2000; Talluri & Narasimhan, 2004).

Untimely deliveries come in the form of early and late deliveries and can be caused by many factors such as port shutdowns due to labor strikes, terrorism, demand fluctuations, stochastic lead times and incorrect shipments. As a result of untimely delivery, the coordination of product flow in the supply chain may be disrupted and can lead to production shutdowns, late deliveries to customers, and increased inventories. As a first step towards implementing a program to improve delivery performance, the costs resulting from untimely deliveries must be identified and quantified.

In this essay, we present a modeling framework that can be used to quantify the financial impact of untimely delivery in a supply chain. This essay contributes to the existing knowledge base of delivery performance by addressing important aspects of overall delivery performance and buyer-supplier integration. First, many delivery performance models in the literature have traditionally evaluated the timeliness of delivery from the shallow perspective of classifying supplier deliveries as being either on-time or not on-time, by comparing the actual lead time to the expected lead time. As an example, Chandra and Grabis (2008) evaluated procurement costs based on variable lead times by classifying deliveries as either on-time or not on-time. We contend that a more comprehensive approach towards measuring delivery performance is possible when the costs due to both early and late deliveries are taken into account.

Second, delivery models are often not linked to the continuous improvement of long term delivery performance (Choi & Hartley, 1996; Guiffrida & Nagi, 2006a). We argue that the timeliness of a supplier's delivery should be modeled as a random variable to allow for a probabilistic assessment of the magnitude (measured in an appropriate time unit) to which a delivery is early, on-time or late. Data collected in this form and represented by an appropriate underlying probability density function can then be utilized by management to proactively manage the supplier delivery function. The resulting probability model of delivery performance can then be used to evaluate opportunities to improve aggregate delivery performance. By equating delivery performance in financial terms (e.g., contractually agreed upon penalty costs for early and late deliveries), the model integrates supplier delivery performance to a resource-based program for the long term continuous improvement of delivery performance.

Optimization methods can be used to determine minimum cost policies in which the costs associated with untimely delivery (earliness and lateness) as well as the investment cost

associated with reducing untimely delivery can be formulated. The flowchart in Figure 5 explains the modeling approach adopted in this chapter for evaluating delivery performance.

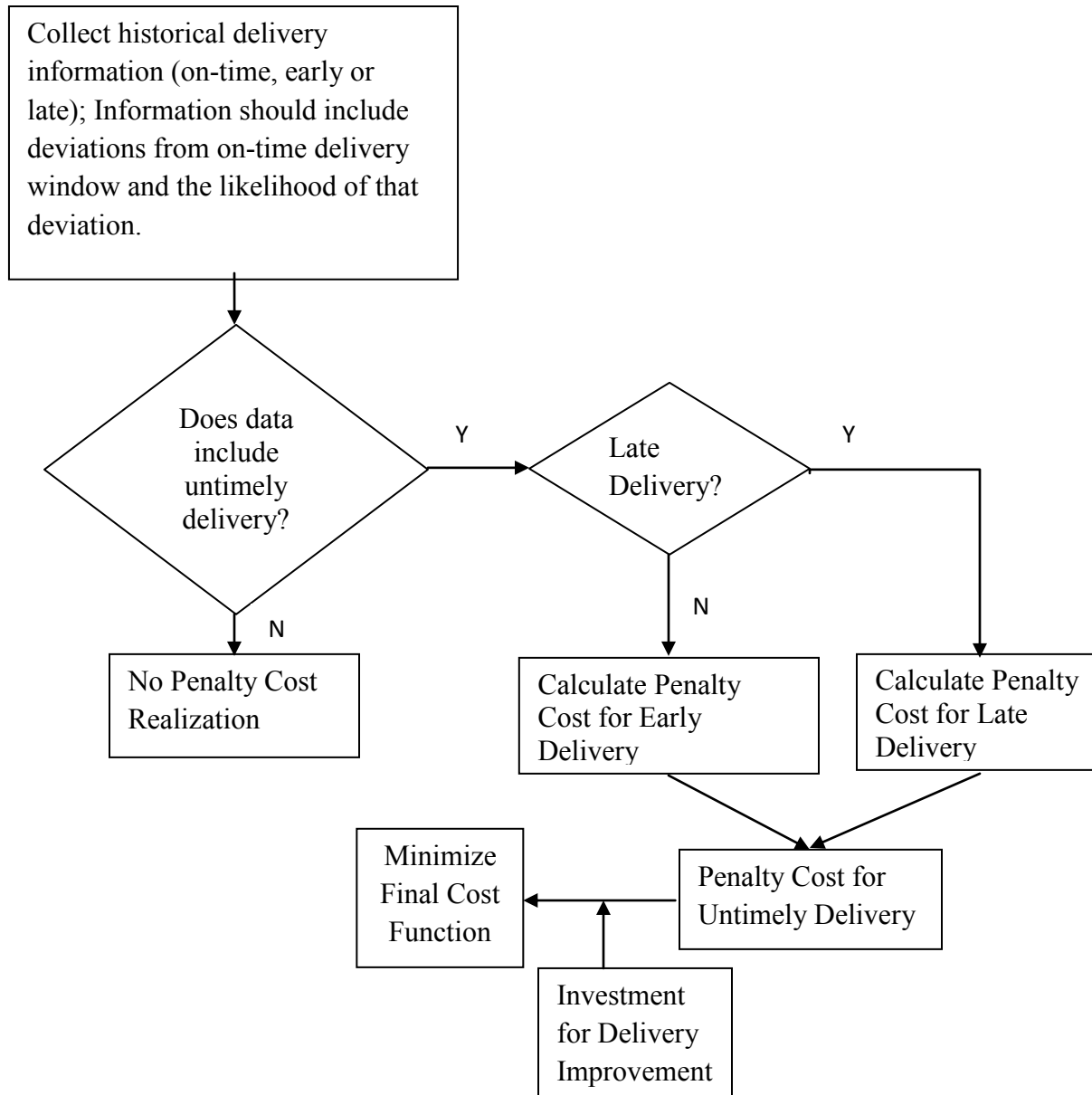


FIGURE 5
Flow Chart for Modeling Penalty Cost for Untimely Delivery

The rest of this essay is organized as follows: Section 3.2 reviews literature on delivery performance models. Section 3.3 introduces a cost-based model for evaluating untimely delivery

using the multinomial probability function. In Section 3.4, a decision framework is introduced that links delivery performance and the financial investment to improve delivery performance. Finally, in Section 3.5, we discuss the contributions to supplier evaluation of the delivery performance model presented herein and conclude with directions for future research.

3.2. Literature Review of Delivery Performance Models

Recent research has identified delivery performance as a key management concern among supply chain managers (Vachon & Klassen, 2002; Min & Zhou, 2003; Lockamy & McCormack, 2004). Conceptual frameworks which classify delivery performance as a strategic level supply chain performance measure are found in Gunasekaran and Kobu (2007), Gunasekaran et al. (2001) and Fawcett et al. (1997). Many empirical studies have validated that delivery performance is a key factor in supplier evaluation decisions and overall firm performance (Olhager & Selldin, 2004; Tan et al., 2002; Salvador et al., 2001; Tracey & Tan, 2001).

Models for evaluating delivery performance to the final customer within multi-stage supply chains have been proposed by several researchers. These models can be classified according to two distinct mathematical modeling approaches. The first class of models employs capability indices to model delivery performance. Garg et al. (2006) utilize a six-sigma statistical design tolerance methodology and create a “delivery capability index” that is similar in structure to the “Cpk” process capability index that is used manufacturing. The index is used to optimally distribute the pool of activity variance that results when manufacturing a product in a multi-stage supply chain so as to satisfy customer delivery expectations with respect to a delivery window which designates early, on-time and late deliveries. Wang and Du (2007) develop a similar six-sigma driven delivery capacity indexing method and define a total cost model for evaluating

delivery performance subject to a customer defined delivery window. The applicability of the model in making supplier selection decisions is demonstrated.

A second class of supply chain delivery performance models are cost-based models that translate the probability of early and late delivery deviations (as measured with respect to a defined delivery window imposed on the probability density function of delivery times) into an expected cost measure. Guiffrida and Jaber (2008) present a budget constrained nonlinear optimization model which captures the expected costs for early and late delivery. Guiffrida and Nagi (2006b) establish bounds for justifying financial investment for improving on-time delivery performance and quantify the impact of failing to invest in improving supply chain delivery performance as the opportunity cost of “managerial neglect”.

The two classes of aforementioned delivery performance models are elegant in their application of statistical theory and mathematical optimization to the task of evaluating supply chain delivery performance. However the models are limited in that they use the normal probability density function to define the distribution of delivery times. Hence, the models have implicitly assumed that the delivery distribution is symmetric when in reality the occurrence of early and late deliveries is rarely the same. In this chapter, we overcome this weakness and present a cost-based model that evaluates the expected cost of untimely delivery using the empirical delivery deviation data and their corresponding probabilities. This simpler yet exact modeling approach can be more easily integrated into a supplier evaluation program and provides more accurate cost information when linking delivery cost analysis to delivery performance.

3.3. Equating Delivery Performance to a Cost Function

In this section we present the mathematical form of a penalty cost model for untimely supplier delivery. We first review the concept of a delivery window and build upon this discussion to introduce the penalty cost model, which is based on the dynamics of the delivery window.

3.3.1. Evaluating Delivery Performance Using an On-Time Delivery Window

Recent research on supply chain delivery performance has investigated the ability of a supply chain to meet the temporal delivery requirements of its end customers using delivery windows (Garg et al., 2006; Wang & Du, 2007; Guiffrida & Jaber, 2008). Metrics based on delivery windows capture the most important aspect of delivery prowess: reliability (Johnson & Davis, 1998). Modeling delivery reliability (i.e. variability), it is argued, is the key to improving delivery prowess, and hence customer satisfaction. Under the concept of a delivery window, the buyer supplies an earliest acceptable delivery date and a latest acceptable delivery date. The width of a delivery window is thus defined as the difference between the earliest acceptable delivery date and the latest acceptable delivery date. Deliveries received within the specified delivery window are considered on-time. A delivery received before the earliest acceptable delivery date is considered early; a delivery received after the latest acceptable delivery date is considered to be late. The magnitude of an early delivery is defined as the deviation between the realized date of delivery and the earliest acceptable delivery date as defined by the delivery window. The magnitude of a late delivery is defined as the deviation between the realized date of delivery and the latest acceptable delivery date as defined by the delivery window.

In modeling the delivery performance of suppliers as a prelude to sourcing and the subsequent translation of delivery performance into cost for continuous improvement, it is imperative that we define our cost function to emphasize cost to the buyer due to the supplier's lack of expected delivery performance. We refer to the costs of *untimely* delivery as “penalty costs” since these costs are levied on the supplier for failing to make the delivery within the acceptable delivery window specified by the buyer. Hence, as part of a continuous improvement program to improve supplier performance, the penalty costs incurred for untimely delivery provides a useful and easy to understand metric for benchmarking improvements in the supplier's overall delivery performance. Figure 6 illustrates the delivery window and penalty considerations pertaining to this window.

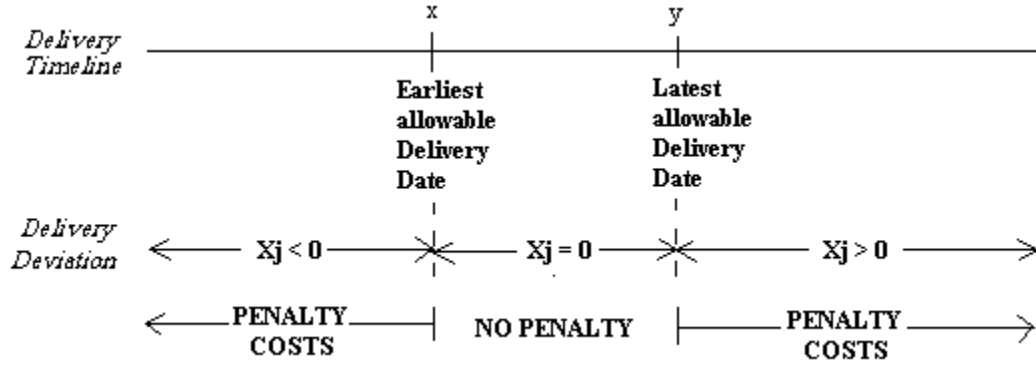


FIGURE 6
Delivery Window and Penalty Considerations

As illustrated in Figure 6, “x” and “y” represent the earliest acceptable and latest acceptable delivery times, respectively. Thus when the supplier delivers within this acceptable delivery window (i.e., anywhere between points x and y in Figure 6), the delivery is considered on-time, and since there is no deviation from the buyer's expected on-time delivery window, the time duration of this deviation for the j-th delivery is zero, i.e., $X_j = 0$. Hence, there is no associated

penalty. Deliveries outside of the delivery window imply earliness ($X_j < 0$) or lateness ($X_j > 0$), both of which render penalty costs.

3.3.2. A Multinomial Probability Model for Supplier Delivery Performance

Many supplier evaluation models evaluate delivery performance from the perspective of whether a delivery was made “on-time” or “not on-time”, thereby suggesting a binomial type process. Consider an example where a buyer sources a component from two different suppliers, A and B. Each supplier fails to deliver within the buyer’s prescribed delivery window with supplier A delivering early and supplier B delivering late. In the traditional binomial based evaluation process where deliveries are characterized as on-time vs. not on-time, the deliveries from both suppliers A and B are considered “not on-time” and are categorized as the same type of event. In reality, early delivery from supplier A leads to holding costs of inventory at the buyer’s end, while late delivery from supplier B may lead to costs associated with production shortages and loss of goodwill. Hence, it is important to separate early deliveries from late deliveries to preserve their unique impacts on supply chain coordination and costs. To accomplish this, we generalize the modeling of delivery performance from a binomial modeling perspective to that of a multinomial perspective thus allowing for the unique magnitudes of earliness and lateness of untimely deliveries to be captured.

Consider a series of N deliveries where the delivery timeliness of each delivery is evaluated based on a stated delivery window. Each delivery is considered to be an independent trial in which one of k mutually independent delivery deviations X_1, X_2, \dots, X_k can be observed. The joint distribution of the random variables n_1, n_2, \dots, n_k which represent the frequency of

occurrences of the delivery deviations X_1, X_2, \dots, X_k over the N deliveries is defined by the multinomial distribution

$$P(n_1, n_2, \dots, n_k) = N! \prod_{j=1}^k \left(\frac{p_j^{n_j}}{n_j!} \right) \quad (3-1)$$

where the parameter p_j equals the probability of delivery deviation X_j for each trial. The multinomial probability model is constrained subject to the following conditions:

$$\sum_{j=1}^k p_j = 1, \sum_{j=1}^k n_j = N, n_j \geq 0.$$

Numerical Illustrations. Consider a supplier whose historical delivery performance has resulted in the following $k = 6$ possible delivery deviations for a given delivery window.

Delivery Deviation X_j (in days)	-3 (early)	-2 (early)	-1 (early)	0 (on-time)	1 (late)	2 (late)
Probability p_j	0.03	0.07	0.12	0.50	0.17	0.11

Numerical Illustration 1. Determine the probability P that the next five deliveries that this supplier will make will all be on-time deliveries. This implies that $N = 5$, $n_4 = 5$ and

$n_1 = n_2 = n_3 = n_5 = n_6 = 0$. Evaluating (3-1) yields

$$P = P(0,0,0,5,0,0) = 5! \left[(1)(1)(1) \left(\frac{0.50^5}{5!} \right) (1)(1) \right] = 0.0313.$$

Numerical Illustration 2. Determine the probability P that the next $N = 3$ deliveries made by this supplier are received on-time or at most one day late. This implies that $N = 3$,

$$n_1 = n_2 = n_3 = n_6 = 0 \text{ and } n_4 + n_5 = 3.$$

Evaluating (1) yields $P = P(0,0,0,3,0,0) + P(0,0,0,2,1,0) + P(0,0,0,1,2,0) + P(0,0,0,0,3,0)$

$$P = 3! \left\{ \left[\left(\frac{0.50^3}{3!} \right) + \left(\frac{0.50^2}{2!} \right) (0.17) + (0.50) \left(\frac{0.17^2}{2!} \right) + \left(\frac{0.17^3}{3!} \right) \right] \right\} = 0.3008.$$

Maximum Likelihood Estimates of the Multinomial Model Parameters. Given a historical data set of a supplier's delivery performance as measured in deviations from a required delivery window, the method of maximum likelihood estimation (MLE) may be used to determine the parameter estimates for the underlying multinomial model that is most likely to have produced this observed data. Restating (3-1) to reflect the unknown parameters to be estimated yields

$$P(n_1, n_2, \dots, n_k | p_1, p_2, \dots, p_k) = N! \prod_{j=1}^k \left(\frac{p_j^{n_j}}{n_j!} \right) \quad (3-2)$$

The likelihood function for (3-2) can be defined; however, it is mathematically convenient to work with the natural log of the likelihood function. Since the natural log is a monotonic transformation, the estimates resulting from the log-likelihood function are no different than those of the likelihood function. The log-likelihood function for (3-2) is

$$l(p_1, p_2, \dots, p_k) = \ln(N!) - \sum_{j=1}^k \ln(n_j) + \sum_{j=1}^k n_j \ln(p_j). \quad (3-3)$$

Maximizing (3) subject to $\sum_{j=1}^k p_j = 1$ will be a constrained optimization problem which can be solved by using Lagrange multipliers. Introducing the Lagrange multiplier λ , the objective is to determine the parameter estimates p_1, p_2, \dots, p_k that maximizes

$$L(p_1, p_2, \dots, p_k, \lambda) = l(p_1, p_2, \dots, p_k) + \lambda \left(1 - \sum_{j=1}^k p_j \right). \quad (3-4)$$

For all j , the partial derivatives of (3-4) with respect to p_j take the general form

$$\frac{\partial L(\cdot)}{\partial p_j} = \frac{n_j}{p_j} - \lambda. \quad (3-5)$$

Setting (3-5) equal to zero and solving gives $n_j/p_j = \lambda$ which implies that the maximum likelihood estimates for p_j are proportional to the frequencies n_j with $\lambda = 1/n$ defining the factor of proportionality. Hence, the relative frequency for delivery deviation outcome n_j defines the maximum likelihood estimator for outcome probability p_j . The MLE of p_j for all j are

$$\hat{p}_j = \frac{n_j}{N}. \quad (3-6)$$

Confidence intervals for parameter estimates. Confidence intervals for multinomial proportions (p_1, p_2, \dots, p_k) have been proposed by several researchers and demonstrated in many diverse areas of research such as statistical quality control, marketing research and the medical and biological sciences. May and Johnson (1997) reviewed and compared the performance of several different methods for constructing confidence intervals for multinomial proportions. Based on a

simulation study, May and Johnson recommend the Goodman (1965) intervals for applications when $k \geq 2$ and the number of observations $n_k > 5$.

3.3.3. A Penalty Cost Model for Untimely Delivery

When a supplier's delivery is not made on-time, the buyer experiences extra costs due to untimely delivery. It is a common purchasing agreement practice to allow the buyer to charge suppliers the costs incurred for untimely deliveries (Min & Zhou, 2003). Our model penalizes the supplier for any deviation (either early or late) from the prescribed delivery window by using a modified version of Taguchi's quality loss function (QLF), which has been used extensively in the quality, service, and accounting literatures (Taguchi & Clausing, 1990; Kim & Liao, 1994). The Taguchi loss function has also been used in supplier evaluation and selection by looking at an aggregate loss due to speed, cost, quality, and reliability (Pi & Low, 2006). In penalizing early and late deliveries, we use a QLF approach and specifically use a one-sided modified Taguchi-type loss function to understand penalty costs due to late deliveries.

The QLF approach is different from the traditional defective-non defective dichotomy approach in estimating hidden quality costs for a product. The dichotomy approach considers no hidden quality cost for all units within the specification limits and a certain quality cost for all units outside the specification limit. The QLF approach measures hidden quality costs for *any variation of the actual value from the target value* of a designated product characteristic. This QLF concept fits well into our design of penalty costs for untimely delivery, where the target value is a deviation of $X_j = 0$, i.e. within the delivery window, and any deviation from the delivery window is penalized. The following sections discuss the development of a penalty cost function due to both early and late deliveries.

Penalty Cost for Early Delivery. Early delivery of a product leads to its unintended storage in a warehouse, thereby increasing the holding/carrying costs of inventory at the buyer's end. In a dynamic environment where supply chains around the world are struggling to optimize their entire logistics by mitigating risks associated with their key expected bottlenecks (as an example, a warehouse working at excess capacity due to excess inventory), early delivery from a supplier further contributes towards bottlenecks in the buyer's downstream supply chain by clogging warehouses (Wang & Toktay, 2008). Such bottlenecks lead to holding costs of inventory at the buyer's end that need to be translated back to the supplier as a penalty cost of early delivery.

We thus define our penalty cost of early delivery as a linear function of the number of time units by which the delivery is early; the latter is measured as a deviation from the delivery window, and is denoted as X_j for the j -th delivery.

$$C_{early_j} = (C_1) (X_j) \quad (3-7)$$

Where C_{early_j} = Total penalty cost due to the j -th delivery that is "early"

C_1 = Penalty cost per unit time for any early delivery

X_j = Time duration of the delivery deviation for the j -th delivery

Penalty Cost for Late Delivery. Typically, the case of a late delivery is much more significant, and in reality, more common. With supply chains spanning the globe, risks of operational disruptions are gradually becoming less controllable and more costly. Late deliveries contribute to costs due to expedited delivery and the use of labor and materials in the process to maintain business continuity, costs due to changed infrastructure to support this sudden response, potential production stoppages (or buffer inventory maintained in anticipation to prevent potential

production stoppages), potential loss of market share, and worse, loss of goodwill and reputation leading to customer dissatisfaction. Such unintended shifts and balancing of the existing infrastructure at the buyer's end comes at a price.

We agree with Taguchi's QLF and contend that such costs cannot be a simple linear function of the delay. In essence, higher the deviation due to lateness, higher the cost, and vice versa. Thus we define our penalty cost due to late delivery as a one-sided Taguchi-type quadratic function of the late delivery deviation, i.e. X_j . The total cost of a late delivery is defined by:

$$C_{late_j} = (m) (X_j)^2 \quad (3-8)$$

Where C_{late_j} = Total penalty cost due to the j-th delivery that is "late"

m = A proportionality constant depending on the buyer organization's penalty cost structure for late deliveries, and

X_j = Time duration of the delivery deviation for the j-th delivery

Before using equation (3-8) to calculate the penalty due to a late delivery, the value of the proportionality constant (m) must first be estimated. A larger value of m implies a more sensitive penalty function or a steeper parabola. Therefore the size of m determines the slope of the penalty function due to lateness. If the latest allowable delivery day ("y", see Figure 5) and the penalty cost of delivering with a deviation of $[y - (x+y)/2]$ is known, where $(x+y)/2$ is the middle point in the delivery window; then following Taguchi's QLF, the value of m can be estimated by dividing the penalty cost due to this deviation by the squared deviation as shown below:

$$m = (C_2) \{y - (x+y)/2\} / \{y - (x+y)/2\}^2 \quad (3-9)$$

where C_2 = Penalty cost per unit time for a late delivery

y = latest allowable delivery day

$(x+y)/2$ = middle point of the delivery window

Equation (3-9) may be simplified by defining the width of the delivery window as $d = y - x$ (from Figure 6). Thus (3-9) can be re-written in terms of the proportionality constant (m) as:

$$m = \{(C_2) (y - x)/2\} / \{(y - x)/2\}^2$$

$$= 2C_2/(y-x)$$

$$m = 2C_2/d \tag{3-10}$$

where $d = y - x$; the width of the delivery window (see Figure 6).

Substituting (3-10) into (3-8), we can now re-state (3-8) as follows:

$$C_{late_j} = [2C_2 / d] (X_j)^2 \tag{3-11}$$

A Multinomial Probability Penalty Cost Function for Untimely Delivery. Building on equation (3-1) and combining equations (3-7) and (3-11), we define the following model for measuring the expected penalty cost associated with a delivery. Let

$$C = \sum_{j=1}^k \left(\hat{p}_j \right) (\beta) \left[\frac{(2)(C_2)}{d} \{(X_j)^+\}^2 - (C_1)(X_j)^- \right] \tag{3-12}$$

where

C = expected penalty cost associated with a delivery

C_1 = penalty cost per unit time for an early delivery

C_2 = penalty cost per unit time for a late delivery

j = the delivery deviation index; $j = 1, 2, 3 \dots k$

X_j = the time duration of the j -th delivery deviation

($X_j = 0$ if on-time, $X_j < 0$ if early, $X_j > 0$ if late)

X^+ = $\max (X, 0)$

X^- = $\min (X, 0)$

\hat{p}_j = the MLE for the probability of the j^{th} delivery deviation

d = width of the delivery window

β = a supply risk parameter ($0 < \beta \leq 1$)

In reference to the model defined in equation (3-12), we note the following:

- X^+ and X^- are indicator variables such that for any delivery, only the early or the late penalty is activated, and not both. Thus for $X_j > 0$, the late penalty function is activated and early penalty function is turned off. For $X_j < 0$, the early penalty function is activated and the late penalty function is turned off. Finally, when $X_j = 0$, both early and late penalty functions are turned off.
- β is assigned by the buyer management to “tune” the untimely delivery penalty based on supply risk, which in turn build on supplier reputation, importance of the sourced product/part to the buyer’s business, the supplier’s compatibility and/or inclination

towards meeting environmental sustainability standards as set by the buyer, and risks associated with delivery from the supplier. Thus, $\beta = 1$ implies maximum risks and hence least reward (due to higher penalty costs). As β decreases, the penalty cost reduce by the same proportion (3-12), thereby rewarding the supplier for reduced supply risks.

Numerical Illustration. Let us suppose that the historical information pertaining to a supplier's delivery deviation and associated likelihood of delivery is given for $k = 6$ as follows:

Delivery Deviation X_j (in days)	-2	-1	0	1	2	3
Probability \hat{p}_j	0.1	0.2	0.4	0.1	0.15	0.05

Let us also assume that the buyer management has furnished the following information:

$C_1 = 100$; $C_2 = 400$; $\beta = 0.5$; delivery window, $d = 4$ days

Substituting this information into (3-12) yields:

$$C = \sum_{j=1}^k (\hat{p}_j)(0.5) \left[\frac{(2)(400)}{4} \{(X_j)^+\}^2 - (100)(X_j)^- \right]$$

$C = 135$.

Thus the expected penalty cost for an untimely delivery by this supplier, given the supplier's historical delivery data, the buyer management's consideration of penalty costs, and a four-day delivery window amounts to \$135.

We use the historical information of the supplier provided in the numerical illustration to investigate multiple scenarios using the model in light of different profiles of two parameters

used in the model - the delivery window (d) set by the buyer, and the level of risk associated with a supplier (β). Using the penalty cost model established in (3-12), Table 4 provides a synopsis of the penalty cost dynamics for different values of “d” and “ β ”. Figure 7 represents the data of Table 4 in a pictorial form using the penalty cost as a surface response.

Delivery Window (d)	Supply Risk (β)				
	0.15	0.35	0.55	0.75	0.95
2	\$75	\$175	\$275	\$375	\$475
4	\$41	\$95	\$149	\$203	\$257
6	\$29	\$68	\$106	\$145	\$184
8	\$23	\$54	\$85	\$116	\$147
10	\$20	\$46	\$73	\$99	\$125

TABLE 4
Financial Impact of Untimely Delivery for Different Parameter Profiles

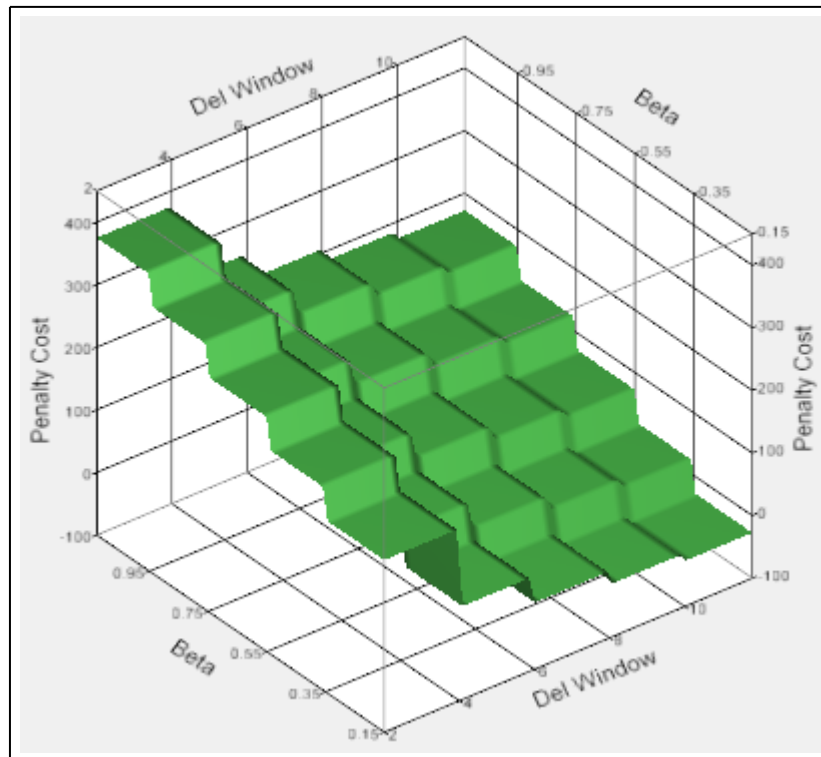


FIGURE 7
Surface Response Plot of Penalty Cost for different Parameter Profiles

Table 4 supports the utilization of our penalty cost model in its ability to provide a decision rubric in the hands of practitioners to incorporate redundancy in supplier selection strategy as a means of mitigation against sudden disruptions in the supply chain. Global suppliers with different delivery windows and varying levels of adherence to buyer expectations can pool delivery penalty cost data to establish a supply base. This supply base can then be used to cater to a specific level of penalty cost that is admissible by the buyer as defined by the buyer's budget constraints. Multiple suppliers chosen in this process will create redundancy in the supply base to

mitigate supply risks associated with global sourcing. The specific dynamics of Table 4 are discussed in detail in section 3.5.

3.4. A Methodology to Minimize Costs Associated with Untimely Delivery

Data on delivery performance subject to a delivery window is discrete. As seen in the delivery performance literature discussed earlier, researchers have used the normal probability distribution to model delivery times. This modeling approach may be weakly justified by the argument set forth in Hall (1986), that data defining a normal distribution is essentially discrete in the sense that each data point is distinct from the others when viewed to a fixed number of significant digits. When the number of discrete data values is large enough, a continuous function can closely approximate a discrete function or discrete data. While discrete models are easy for the computer to process, continuous approximations are useful in developing models that are easy for humans to comprehend and interpret. Discrete and continuous models do not compete with each other; they complement each other to best address a purpose or situation.

Approximating discrete data points with continuous density functions is a common practice that has well been established in the logistics literature for more than four decades (Box & Jenkins, 1970; Newell, 1973; Guiffrida, 1999). In this section we introduce a continuous model for approximating the multinomial expected penalty cost model developed in Section 3.3.3 to facilitate a more efficient and modeling-friendly optimization framework for incorporating the cost of investment for untimely delivery into the decision making process.

3.4.1. Modeling Delivery Performance using the Asymmetric Laplace Density

Our approximating model is based on the asymmetric Laplace probability density function. The asymmetric Laplace penalty cost model proposed in this dissertation has two advantages

over penalty cost models that are based on the normal probability density function which have been reported in the literature for approximating empirical delivery data. First, the asymmetric Laplace density may be symmetric or skewed depending on the values specified for its parameters thus allowing a more realistic representation of the delivery deviation. Second, the expected asymmetric Laplace penalty cost model exists in closed form thus supporting optimization procedures.

Kozubowski and Podgorski (2000) define the probability density function and distribution function of the asymmetric Laplace density as

$$f_x(x; \theta, p, k) = \frac{k}{p(1+k^2)} \begin{cases} \exp\left\{-\frac{k}{p}(x-\theta)\right\} & x \geq \theta \\ \exp\left\{\frac{1}{pk}(x-\theta)\right\} & x < \theta \end{cases} \quad (3-13)$$

and

$$F_x(x; \theta, p, k) = \begin{cases} 1 - \frac{1}{1+k^2} \exp\left\{-\frac{k}{p}(x-\theta)\right\} & x \geq \theta \\ \frac{k^2}{1+k^2} \exp\left\{\frac{1}{pk}(x-\theta)\right\} & x < \theta \end{cases} \quad (3-14)$$

for $-\infty < x < \infty$, location parameter $\theta \in (-\infty, \infty)$, shape parameter $p > 0$ and skewness parameter $k > 0$. Maximum likelihood estimators for the parameters of the asymmetric Laplace density may be found in Ayebo (2002). On time delivery (i.e., within a delivery window between c_1 and c_2 ; and hence a delivery deviation of zero) can be captured in the asymmetric Laplace penalty cost model by defining $F^{-1}(c_2) - F^{-1}(c_1) = p(X = 0)$ for $c_2 > c_1$. We assume that the

delivery process is stable enough such that the modal delivery deviation is zero thus $\theta = 0$.

Figures 8a through 8d illustrates the asymmetric Laplace density for varying values of the shape and skewness parameters for location parameter $\theta = 0$.

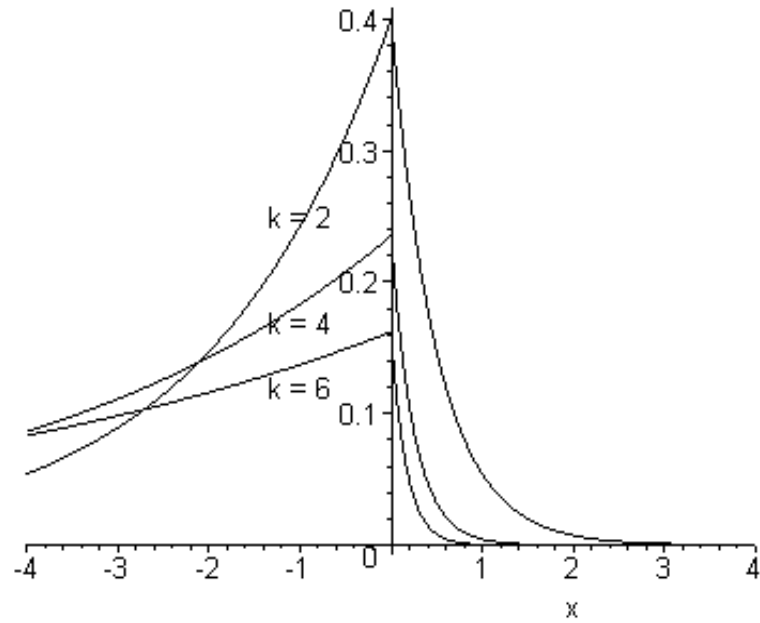


FIGURE 8a
Asymmetric Laplace Density for $p = 1, k = 2, 4, 6$.

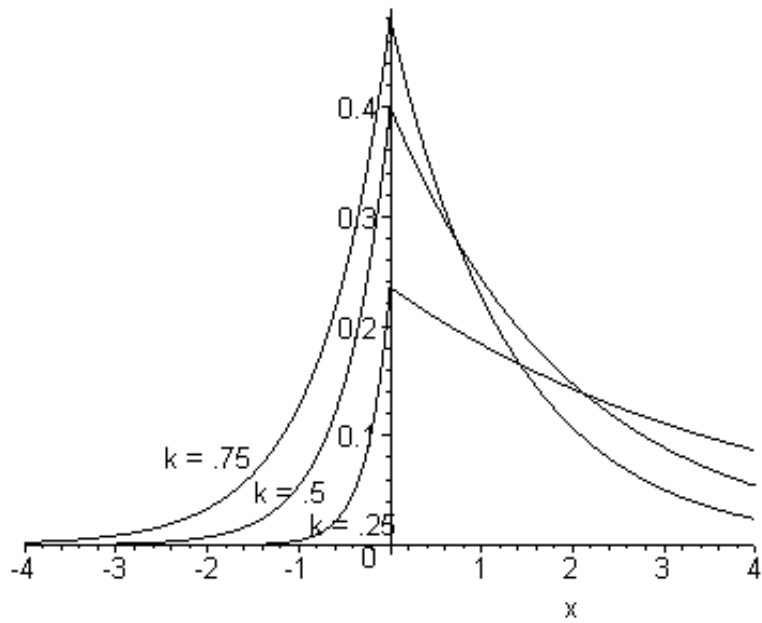


FIGURE 8b
Asymmetric Laplace Density for $p = 1$, $k = 0.25, 0.5, 0.75$.

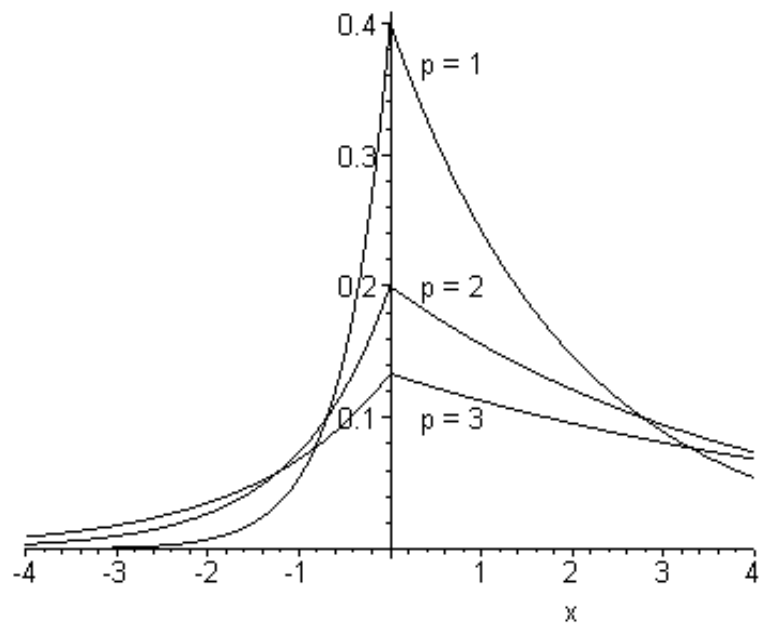


FIGURE 8c
Asymmetric Laplace Density for $k = 0.5$, $p = 1, 2$, and 3

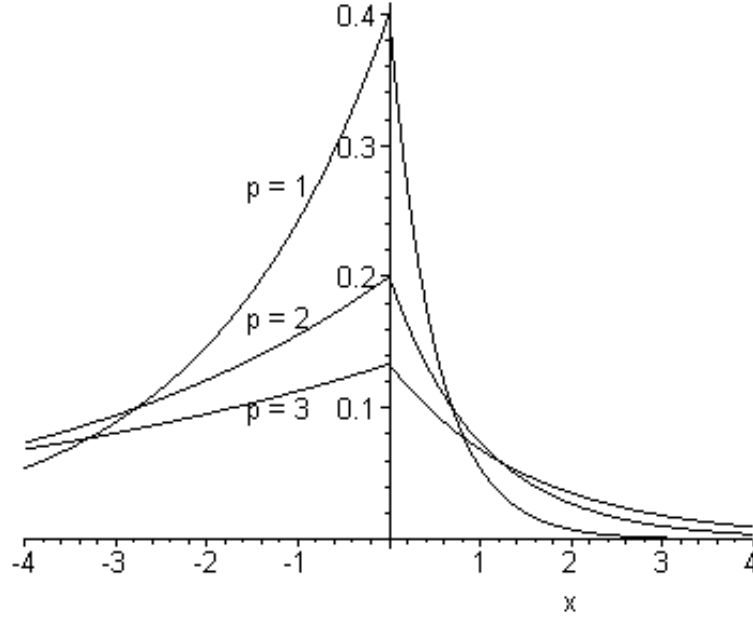


FIGURE 8d
Asymmetric Laplace Density for $k = 2$, $p = 1, 2$, and 3

The general form of an approximating continuous penalty cost model (Guiffrida & Nagi, 2006a) is

$$Y = C_1 \int_{-\infty}^{c_1} (c_1 - x) f_X(x) dx + C_2 \int_{c_2}^{\infty} (x - c_2) f_X(x) dx \quad (3-15)$$

where C_1 = earliness cost

C_2 = lateness cost

$f_X(x)$ = density function of delivery time X

The first integral in (3-15) evaluates the expected earliness cost; the second integral in (3-15) evaluates the expected lateness cost. In line with the multinomial penalty cost model defined in the earlier section, we maintain the same form of penalty considerations in the continuous model, i.e., a linear approach to penalty for early delivery and a quadratic approach to penalty for late delivery. We thus restate (3-15) as follows:

$$Y = C_1 \int_{-\infty}^{c_1} (c_1 - x) f_X(x) dx + C_2 \int_{c_2}^{\infty} (x - c_2)^2 f_X(x) dx \quad (3-16)$$

Introducing the probability density function of the asymmetric Laplace into (3-16) with $c_1 \leq \theta \leq c_2$ yields the following:

$$Y = \frac{C_1 k}{p(1+k^2)} \int_{-\infty}^{c_1} (c_1 - x) e^{\frac{x-\theta}{kp}} dx + \frac{C_2 k}{p(1+k^2)} \int_{c_2}^{\infty} (x - c_2)^2 e^{-\frac{k(x-\theta)}{p}} dx. \quad (3-17)$$

The expected penalty cost expression defined by (3-17) is separable in terms of the expected earliness and lateness costs. The expected lateness term may be rewritten as:

$$Y_{Late} = \frac{C_2 k}{p(1+k^2)} \left[\int_{c_2}^{\infty} x^2 e^{-\frac{k(x-\theta)}{p}} dx - 2c_2 x \int_{c_2}^{\infty} e^{-\frac{k(x-\theta)}{p}} dx + c_2^2 \int_{c_2}^{\infty} e^{-\frac{k(x-\theta)}{p}} dx \right]. \quad (3-18)$$

Let $u = \frac{k(x-\theta)}{p}$, $du = \frac{k dx}{p}$ and $x = \frac{up}{k} + \theta$.

Introducing these substitutions into (3-18) gives

$$\begin{aligned} Y_{Late} &= \frac{C_2 k}{p(1+k^2)} \left[\int_{\frac{k(c_2-\theta)}{p}}^{\infty} \left(\frac{up}{k} + \theta \right)^2 e^{-u} \frac{p}{k} du - 2c_2 \int_{\frac{k(c_2-\theta)}{p}}^{\infty} \left(\frac{up}{k} + \theta \right) e^{-u} \frac{p}{k} du + c_2^2 \int_{\frac{k(c_2-\theta)}{p}}^{\infty} e^{-u} \frac{p}{k} du \right] \\ &= \frac{C_2}{(1+k^2)} \left[\left(\frac{p}{k} 2e^{-u} \left(\frac{up}{k} + \theta \right) \right) - \left(\frac{up}{k} + \theta \right)^2 e^{-u} \right]_{\frac{k(c_2-\theta)}{p}}^{\infty} \\ &\quad - 2 \frac{c_2 p}{k} \left(e^{-u} - u e^{-u} \right) \left(-e^{-u} \right) \Big|_{\frac{k(c_2-\theta)}{p}}^{\infty} + \left(c_2^2 - 2c_2 \theta \right) \left(-e^{-u} \right) \Big|_{\frac{k(c_2-\theta)}{p}}^{\infty} \end{aligned}$$

$$= \frac{C_2}{(1+k^2)} \left[(2c_2^2 - 4c_2\theta) e^{-\frac{k(c_2-\theta)}{p}} \right]$$

$$Y_{Late} = \frac{C_2}{k(1+k^2)} 2 \left\{ (c_2 - \theta)^2 - \theta^2 \right\} e^{-\frac{k(c_2-\theta)}{p}} \quad (3-19)$$

By similar mathematical analysis, it can be shown that the expected earliness term is

$$Y_{Early} = \frac{C_1 p}{k(1+k^2)} e^{-\left(\frac{\theta-c_1}{pk}\right)} \quad (3-20)$$

Combining (3-19) and (3-20) gives

$$Y = \frac{1}{k(1+k^2)} \left[C_1 p e^{-\left(\frac{\theta-c_1}{pk}\right)} + 2C_2 \left\{ (c_2 - \theta)^2 - \theta^2 \right\} e^{-\frac{k(c_2-\theta)}{p}} \right] \quad (3-21)$$

Lemma 1. *For a fixed location parameter $c_1 \leq \theta \leq c_2$, the total expected penalty cost is a convex function of the shape parameter (p) for asymmetric Laplace distributed delivery.*

Proof. With no loss of generality let $c_2 - \theta = -(c_1 - \theta) = \delta$. The total expected penalty cost per period as a function of the shape parameter is

$$Y(p) = \frac{1}{k(1+k^2)} \left[C_1 p e^{-\left(\frac{\delta}{pk}\right)} + 2C_2 \left\{ \delta^2 - \theta^2 \right\} e^{-\frac{k\delta}{p}} \right]. \quad (3-22)$$

$$Y(p) = \frac{1}{k(1+k^2)} \left[C_1 p e^{-\left(\frac{\delta}{pk}\right)} - 2C_2 c_1 c_2 e^{-\frac{k\delta}{p}} \right]. \quad (3-23)$$

The first and second derivatives of $Y(p)$ are

$$Y'(p) = \frac{1}{k(1+k^2)} \left[C_1 e^{-\left(\frac{\delta}{pk}\right)} \left\{ 1 + \frac{\delta}{pk} \right\} - 2C_2 c_1 c_2 e^{-\frac{k\delta}{p}} \frac{k\delta}{p^2} \right] \quad (3-24)$$

and

$$Y''(p) = \frac{\delta}{k(1+k^2)p^3} \left[C_1 e^{-\left(\frac{\delta}{pk}\right)} \frac{\delta}{k^2} - 2kC_2c_1c_2 e^{-\frac{k\delta}{p}} \left\{ 2 - \frac{k\delta}{p} \right\} \right]. \quad (3-25)$$

Examining (3-25), we note that for positive values of C_1, C_2, p, k and δ , $Y''(p) > 0$ subject to

$\frac{k\delta}{p} \leq 2$. Hence the expected penalty cost is a convex function of the shape parameter p provided

that $p \geq \frac{k\delta}{2}$.

3.4.2. Minimizing Penalty Costs for Untimely Delivery

An optimization model which considers the shape parameter p as a decision variable is defined in this section. The objective of the model is to determine the value of p that minimizes the costs (expected earliness and lateness) associated with untimely delivery and the investment cost required for reducing p .

A logarithmic investment cost function is used to model the cost of reducing the shape parameter. Under this investment function, reducing the shape parameter by a fixed percentage requires a fixed amount of investment. This functional form is appealing in that each additional reduction in p is more costly than the previous reduction. The logarithmic investment function has been widely adopted in the literature (Cho & Gerchak, 2005; Leschke & Weiss, 1997; Porteus, 1985).

Let p_0 equal the current value of shape parameter and λ represent the cost of reducing p by h percent. The investment function is then

$$C(p) = \frac{\lambda}{\ln(1/h)} [\ln(p_0) - \ln(p)] \quad \text{for } 0 < p \leq p_0. \quad (3-26)$$

Lemma 2. The investment function is a convex function of the shape parameter p .

Proof. The first and second derivatives of (3-26) are

$$C'(p) = -\frac{\lambda}{\ln(1/1-h)p}, \quad (3-27)$$

and

$$C''(p) = \frac{\lambda}{\ln(1/1-h)p^2}. \quad (3-28)$$

Examining (3-27) and (3-28) we observe that $C'(p) < 0$ and $C''(p) > 0$ for $\lambda > 0$ and $h > 0$.

The optimization model is

$$\text{Minimize } G(p) = Y(p) + C(p) \quad (3-29)$$

where

p = shape parameter of the delivery distribution

$Y(p)$ = expected penalty cost due to untimely delivery

$C(p)$ = investment required for a shape parameter of p .

Substituting (3-21) and (3-26) into (3-29), yields the optimization model

$$\begin{aligned} \text{Minimize } G(p) = \frac{1}{k(1+k^2)} & \left[C_1 p e^{-\left(\frac{\theta-c_1}{pk}\right)} + 2C_2 \left\{ (c_2 - \theta)^2 - \theta^2 \right\} e^{-\frac{k(c_2-\theta)}{p}} \right] \\ & + \frac{\lambda}{\ln(1/1-h)} [\ln(p_0) - \ln(p)]. \end{aligned} \quad (3-30)$$

Theorem 1. $G(p)$ is a convex function of the shape parameter p for $p \geq \frac{k\delta}{2}$.

Proof. Per Lemma 1 and Lemma 2, $G(p)$ is the sum of two convex functions and is therefore convex.

The first and second derivatives of (3-30) with respect to p are

$$G'(p) = \frac{1}{k(1+k^2)} \left[C_1 e^{-\left(\frac{\delta}{pk}\right)} \left\{ 1 + \frac{\delta}{pk} \right\} - 2C_2 c_1 c_2 e^{-\frac{k\delta}{p}} \frac{k\delta}{p^2} \right] - \frac{\lambda}{\ln(1/(1-h))p} \quad (3-31)$$

and

$$G''(p) = \frac{\delta}{k(1+k^2)p^3} \left[C_1 e^{-\left(\frac{\delta}{pk}\right)} \frac{\delta}{k^2} - 2kC_2 c_1 c_2 e^{-\frac{k\delta}{p}} \left\{ 2 - \frac{k\delta}{p} \right\} \right] + \frac{\lambda}{\ln(1/(1-h))p^2}. \quad (3-32)$$

Examining (3-32), we note that for positive values of $C_1, C_2, p, k, h, \lambda$, and δ , $Y''(p) > 0$ subject to $\frac{k\delta}{p} \leq 2$. Hence $G(p)$ is a convex function of the shape parameter p ; where $p \geq \frac{k\delta}{2}$. At the

value of the shape parameter p^* , we have found the optimal reduction in the expected penalty cost $Y(p)$ for an investment cost of improvement $C(p)$.

Numerical Illustration. Let us suppose that the parameters associated with the shape of the asymmetric Laplace distribution are as follows:

$0.25 \leq k \leq 0.9$; where k is the skewness parameter of the asymmetric Laplace distribution

$k\delta/2 \leq p \leq p_0$; where p is the shape parameter of the asymmetric Laplace distribution

Further, let us suppose that the buyer management has put forward the following constraints:

- $C_1 = 100$; $C_2 = 400$
- It is expected that the delivery process is stable enough such that the modal delivery deviation is zero, i.e. $\theta = 0$, where θ is the location parameter of the asymmetric Laplace distribution
- $3 \leq \delta \leq 14$; i.e. a delivery deviation from 3 up to 14 will be considered
- The cost of reducing the shape parameter p by 10 % (i.e., $h = 0.10$) is 20, i.e. $\lambda = 20$

Optimization in LINGO yields an objective function of 756.75, for shape parameter p equaling 1.35, skewness parameter k equaling 0.9, and a delivery deviation of 3. The program and output are available in Appendix C.

3.5. Discussion and Conclusions

Several researchers have identified the need to link supply chain performance with cost (Lalonde & Pohlen, 1996; Schneiderman, 1996; Ballou et al., 2000; Ellram, 2002). The multinomial model for supplier delivery evaluation (and its asymmetrical Laplace approximation) presented in this chapter is supportive of this need and serves to quantify supplier delivery performance in metrics (probability and cost) that is of importance to researchers and practitioners alike. The model presented herein can be used to quantitatively evaluate the delivery performance of a supplier. Analysis can be conducted to investigate the probability to which a supplier can achieve timely delivery with regard to a specified delivery window as well as the expected cost resulting due to untimely delivery. The model also can be used to proactively investigate scenarios in which changes to the existing delivery window are planned. The expected costs associated with a proposed change to the existing delivery window can be

estimated using the model. This cost data may prove useful in justifying the financial investment required for implementing changes to the existing supply chain to reduce the risk of untimely delivery, thereby providing rich implications to both theory and practice.

3.5.1. Implications to Theory and Practice

The penalty cost model for evaluating untimely delivery performance put forward in this paper enriches the supply chain literature in multiple avenues. *First*, this model not only analytically equates supplier performance to cost realization, but also lays a foundation towards the performance traits of successful supply chains as laid out by Lee (2004). Based on the analysis of more than sixty companies, Lee (2004) concluded that top performing supply chains possess three distinct qualities: *agility*, i.e., the ability to respond speedily to sudden changes in demand and/or supply; *adaptability*, i.e., the ability to adapt over time as market structures and strategies evolve; and *alignment*, i.e., the ability to create synergy in the interests of all firms in the supply chain to optimize overall performance.

The goal of all members (buyers and suppliers) in a supply chain is to create the right balance within the chain so that it can provide value to customers with short response times and high service levels while simultaneously maintaining cost efficiencies. Buyer's typically define delivery windows to suppliers by taking into account the agreed delivery time to the next member in the downstream supply chain. With this approach, it is imperative that suppliers deliver within the buyer's prescribed window to avoid late deliveries downstream. Late deliveries in the supply chain eventually lead to customer dissatisfaction, which may result in the buyer's (and the supplier's) loss in market share; early delivery by the supplier leads to the buyer's holding cost of inventory. The penalty cost models defined in this chapter are evaluation

tools that suppliers can use to align themselves with the delivery expectations of a buyer. Thus the models presented herein enhance buyer-supplier alignment by enabling the buyer and supplier to realize their respective needs and enter into a mutual agreement using an easy to understand financial (cost based) metric of delivery performance.

Second, the risk parameter β introduced in this model provides research opportunity in the study of buyer tolerance and control on a supplier's delivery performance. While supply risks have been addressed previously in terms of product position in the life cycle, product importance to buyer, and supplier reputation; risks of supply and supplier propensity towards environmental sustainability have been overlooked in modeling supplier delivery performance. In light of the current and growing environmental concerns over global warming and carbon footprints, this paper proposes that management look at both supply risk considerations as well as supplier's alliance to environmental sustainability to define the risk parameter, β . It would only be in the realm of conjecture to extrapolate from our model and future research and practice might find this study a stepping stone towards a green, risk adjusted delivery performance model.

Third, by addressing penalty costs as a function of the buyer's delivery window as well as a parameter that rewards the supplier by adhering to buyer expectations, this model allows for supplier development initiatives and optimization of the supply base in addition to supplier evaluation. Table 4 was generated using the penalty cost model of equation (3-12) and the historical information pertaining to a supplier's delivery performance from our numerical illustration (Section 3.3). Table 4, in spite of its simplicity based on the assumptions mentioned above, offers an interesting anecdote to an important supplier selection strategy that is core to responsive supply chains - *redundancy* (Sheffi, 2001). Multiple sourcing policies have been widely used to maintain redundancy to mitigate disruptions in the supply chain. As an example,

Motorola Inc. buys many of its handset components from multiple vendors. Doing so prepares the company for disruptions without building up fast-depreciating inventory. Motorola lowers the cost of redundancy by using multiple suppliers for high-volume products.

The analysis illustrated in Table 4 demonstrates how our penalty cost model may be used to incorporate redundancy in the supply base. The table suggests that for a buyer constrained by penalty cost limits in the order of \$145-150, there are three suppliers whose delivery performances lead to penalty costs in this range. The first supplier has a prescribed delivery window of 4 (days) and whose risk is at the 0.55 level. This supplier is presumably a local supplier in the US who leverages its physical distance from the US buyer with its low supply risks but is required to deliver in a tighter window, thereby yielding a penalty cost of \$149. A second supplier has a slightly longer delivery window (6 days), therefore suggesting an international supplier, somewhere in Latin America or Europe who would have higher supply risks ($\beta = 0.75$) but also get a wider delivery window. This supplier yields a penalty cost of \$145. Finally, the third supplier has the widest delivery window (8 days); for the sake of argument we may presume its origin in south Asia, and this supplier has the most risk associated with supply ($\beta = 0.95$). This supplier yields a penalty cost of \$147. Together, the three suppliers provide a comprehensive global sourcing landscape to the buyer to maintain redundancies, given penalty cost constraints in the \$145-150 range. In a similar way, supply landscapes may be drawn for different sets of penalty cost constraints to come up with different *efficient frontiers* of capable suppliers.

Fourth, the expected penalty cost calculated on the basis of a supplier's delivery performance can be used as a starting point of negotiations for future contractual agreements with the supplier.

On the same token, the expected penalty cost may also be used towards negotiations with a new, prospective supplier with similar delivery performance expectations.

Fifth and finally, as discussed in Guiffrida and Paul (2010), the feedback that the model can provide would be useful as part of a supplier development program to improve supplier delivery performance. Our supplier delivery performance evaluation model could prove beneficial in justifying resources for: (i) a buyer providing a rolling forecast to the supplier to show potential demand in the following 12-16 months to better prepare to supply, (ii) the supplier maintaining product on consignment at their warehouse at no cost to the buyer to mitigate the effects of a late delivery, (iii) conducting daily and/or weekly meetings with all parties (buyer and supplier) to establish and maintain delivery schedule, (iv) reviewing historical data of the selected suppliers past delivery performance and averaging the numbers to see how it compares to current lead time established in the enterprising system, (v) establishing an alternate source for items that can serve as a risk mitigation contingency, (vi) implementing vendor management systems that better link the inventory control systems of the buyer and supplier, and (vii) development of a supplier reward system to encourage pinpoint accuracy with respect to the buyer's stated delivery window.

3.5.2. Limitations of the Model

The modeling approach adopted in this paper has the following limitations:

- (i) The expected penalty cost model defined in this paper essentially caters to a single buyer-single supplier study, which may be replicated, case by case, for more than one supplier. While more complex supply chains are multi-echelon models where multiple suppliers and their combined dynamics add to the complexity of sourcing,

we restrict ourselves to the single-buyer-single-supplier study to maintain simplicity of the approach. Future work will look at extending this model towards a multiple-supplier consideration.

- (ii) The model orientation is essentially viewed from a buyer's lens, and
- (iii) The fact that the underlying multinomial probability distribution for our penalty cost model draws strength from historical supplier delivery information suggests that the model works primarily with an existing supply base. However, the results from an existing supplier may be extrapolated to a prospective supplier whose delivery performance expectations closely match that of an existing supplier.

3.5.3. Summary Conclusion

The penalty cost model defined in this chapter establishes the cost incurred to a buyer due to untimely delivery from a supplier. Following a Taguchi type loss function, our cost model penalizes suppliers from any deviation from the buyer's prescribed delivery window. By introducing a continuous model for approximating the discrete expected penalty cost function and optimizing the same, we minimize the costs associated with untimely delivery and present a model of buyer expectations to the supplier, thereby leading to enhanced buyer-supplier alignment as well as overall supply chain performance.

By expressing the impact of earliness and/or lateness into a decision variable, this model creates a foundation for future work in supply base optimization, which may allow for leveraging buyer-prescribed delivery expectations towards maximum performance of the supply chain (by minimizing penalty costs). Thus the model may be used for creating a supply matrix that allows the choice of a (set of) supplier(s) based on delivery expectations and associated demand and

capacity constraints, thereby leading to establishment of an *efficient frontier* for supplier selection.

The following chapter investigates buyer spending for continuous improvement of supplier delivery performance to address supplier capability and supplier management.

CHAPTER 4 (Essay # 3)

INVESTIGATING BUYER INVESTMENT FOR SUPPLIER IMPROVEMENT

Chapter 2 focused on how sourcing activities add value to the overall supply chain. A conceptual framework for *value sourcing* was developed to support the design and implementation of sourcing strategies with a supply chain. In Chapter 3, a penalty cost model for financially quantifying the expected cost of untimely delivery was developed. The model demonstrates *cost realization through supplier performance measures* as illustrated in phase I of our value sourcing framework (Figure 4). In this chapter, we investigate the managerial implications of a buyer who financially invests to improve a supplier's delivery performance. We demonstrate an optimization model for the buyer's investment decision to reduce untimely delivery and illustrate how improving supplier delivery performance leads to better supplier selection and management. We thus analytically demonstrate *decision making from cost analysis* as illustrated in phase II of our value sourcing framework (Figure 4).

4.1. Introduction

The average manufacturing firm spends over 50 percent of its revenues on purchased inputs. With companies continuing to increase the volume of outsourced work across industries, this percentage is likely to rise (Handfield et al., 2006). Consequently, suppliers continue to have a significant impact on the delivery of a buying company's products and/or services, and thus on the buyer's profitability through spending on improvements in supplier delivery performance. Buyers seek continuous improvement (CI) in supplier performance because the outcome of CI enables buyers to remain competitive in their downstream supply chain. Improving supplier

delivery performance is thus of critical importance to buyer-supplier alignment and the deployment of a truly integrated supply chain.

In this paper, a modeling framework is presented that can be used to support the long-term improvement of supplier delivery performance within a supply chain. The optimization model links supplier-delivery-related costs that accrue from untimely (early and late) deliveries to CI in supplier selection and management. These decision outcomes are integral to value sourcing. This paper contributes to improvement of supplier delivery performance in the following ways. *First*, since penalty costs for untimely delivery are incurred based on deliveries scheduled over a period of time, it is imperative that cost analysis based on the penalty cost model consider the time value of money. Our model extends continuous improvement of delivery performance by realizing the true present worth of penalty costs to a buyer due to future untimely deliveries from a supplier. This modeling attribute is essential for justifying financial investment to support CI.

Second, our model addresses supply chain agility by introducing delivery time improvement at the supplier's end. We conceptually show the impact of improving supplier delivery performance when the penalty cost of untimely delivery improves according to an exponential decay function. Second, a zeta transformation of this decay function illustrates improvement in the corresponding expected penalty cost in the light of time value of money. We present different profiles for improving untimely delivery based on different improvement rates. This approach to improving delivery performance reduces overall penalty costs due to untimely delivery as well as increases responsiveness of the supply chain.

Third, our model addresses buyer supplier alignment by incorporating continuous improvement in delivery performance from an integrated buyer-supplier perspective. Continuous

improvement of the buyer is addressed by measuring the financial impact of “buyer neglect”, which explains the opportunity cost of failing to consider penalty costs due to untimely delivery. Continuous improvement of the supplier is based on the underlying contention that improvement comes at a price. We therefore discount the magnitude of the buyer’s investment in delivery improvement as a function of the supplier’s rate of improvement. Suppliers who demonstrate a higher rate of improvement are rewarded with a proportional decrease of the price paid by the buyer for improvement, and vice-versa. In reality, suppliers that improve their delivery performance will incur less penalty costs in the short term and enhance their long-term attractiveness to the buyer by continuously improving their delivery performance.

Fourth and finally, guided by a prescribed budget constraint for continuous improvement, we (i) optimize the amount a buyer invests for spending on CI as a means to gauge a supplier’s ability in meeting an optimum improvement rate and, (ii) determine the optimal point in time where improvement should start. Thus, the optimization model herein contributes a budget-constrained managerial decision tool for evaluating the financial impact to both the buyer and the supplier who engage in a CI program to improve supplier delivery performance.

The rest of this essay is arranged as follows: Section 4.2 provides a theoretical approach to improving delivery performance. In this section, we introduce continuous improvement to our penalty cost model by incorporating present worth and a profile for improving untimely deliveries. The opportunity cost of failing to consider penalty costs for untimely delivery is addressed in Section 4.3. In Section 4.4, we discuss the price paid by the buyer for improvement. Section 4.5 introduces an optimization model for buyer spending to balance the opportunity cost of neglecting improvement and the price paid for improvement. Finally, Section 4.6 discusses implications of this research and provides a summary conclusion.

4.2. A Theoretical Approach to Improving Delivery Performance

We address continuous improvement of delivery performance in two steps. First, due to the realization of costs for future deliveries over a period of time, we utilize the time value of money in understanding the penalty costs in present time due to possible untimely deliveries in the future. Second, we incorporate an element of improvement into our model and redesign our discounted penalty cost function taking into consideration the improvement of suppliers in each delivery. The following subsections discuss these in detail.

4.2.1. Present Worth of Investments for Delivery Improvement

In order that time value of money is addressed, flow of cash over a period of time needs to be considered.

Extending equation (3-12), the expected penalty cost of untimely delivery incurred over N deliveries in a one-year planning horizon is defined as:

$$C_N = (N) \sum_{j=1}^k (\hat{p}_j)(\beta) \left[\frac{(2)(C_2)}{d} \{(X_j)^+\}^2 - (C_1)(X_j)^- \right] \quad (4-1)$$

where C_N = total expected penalty cost incurred over N deliveries, and

N = the number of deliveries

As defined, equation (4-1) does not take into consideration the present worth of penalty costs. As documented in the literature, zeta transforms may be employed to considerable advantage in the modeling and analysis of economic situations involving discrete time series of cash flows (Hill & Buck, 1974; Tanchoco & Buck, 1977). In the context of our analysis of penalty costs due to untimely delivery, we are looking at deliveries from suppliers, which in

reality, are often multiple deliveries over a year. Given the discrete nature of our modeling of delivery deviations, we adopt zeta transforms to capture the present value of the cost stream of delivery penalty costs. Using the zeta transformation provides a more flexible (and thus robust) approach towards capturing the present value of all expected penalty costs due to deliveries made during a year. While traditional discounted cash flow (DCF) calculations work well with a one-year horizon, zeta transforms provide more flexibility in calculating present value of penalty costs from supplier deliveries, especially when multiple suppliers are evaluated at different times over a year for sourcing a single product. The zeta transforms are advantageous to a wide variety of discrete time series in three ways (Hill & Buck, 1974):

- Due to its behavior as a linear operator, a series with an existing transform may be *scaled*
- Due to its behavior such that the translation in the time period domain corresponds to the division in the interest domain, a series with an existing transform may be *translated forward* “b” time units
- By incorporating an *on-off switching operator*, a series with an existing transform can be *turned on* after h time units and *turned off* at k time units.

Thus the most important contribution of the zeta transformation lies in the almost unlimited possibilities it provides in model building. Consider a dual sourcing scenario over a one-year forecasted horizon where supplier A makes deliveries in months three, six, and twelve, while supplier B makes a delivery in month 9. The zeta transform, by virtue of its translational property as well as its on-off switching property can model this scenario with ease. In fact, as seen in equation (4-2) below, the zeta transform is indeed a more generalized form of the traditional DCF method wherein $T = 1$ corresponds to the traditional DCF method.

The zeta transform of the discrete time series $f(nT) = C$ is defined as:

$$TPV(C_N) = \sum_{n=0}^N C(1+iT)^{-n} \quad (4-2)$$

where TPV = Total Present Value

T = Constant length time interval between deliveries

N = number of deliveries

i = interest rate associated with interest conversion-time period T

C = expected penalty cost associated with an untimely delivery; from (3-12).

Under conditions of no improvement in delivery performance, the same penalty cost is incurred for each delivery. This results in a uniform series with a penalty cost flow C. The zeta transformation for such a uniform function is of the general form $f(nT) = C$ that starts at $n = 0$ and is continuous over the infinite time horizon. This is formally defined as:

$$TPV(C_N) = (C)(1 + iT)/(iT) \quad (4-3)$$

Incorporating the on-off switching property of the zeta transform², (4-3) can be rewritten as:

$$TPV(C_N) = (C/i) [(1+i)^{1-u} - (1+i)^{1-v}]; \quad (4-4)$$

where i = interest rate associated with constant length time period, T

N = total number of deliveries

u = starting point of cash flow; turn on of series

² Comparison with traditional DCF: Suppose a deposit of \$100 is made each year starting at the end of second year with the last deposit occurring at the end of tenth year. Using $i = 10\%$, the present value of this cash flow may be obtained by direct substitution of the transform above; where $C = 100$, $i = 0.1$, $h = 2$, and $k - 1 = 10$, i.e., $k = 11$. Thus $TPV(C_N) = 100/0.1 [(1.1)^{1-2} - (1.1)^{1-11}] = 523.54$. Traditional DCF calculations provide the same answer.

$v - 1 =$ ending point of cash flow ($v-1 = N$); series is turned off at v

For a complete derivation of equations (4-3) and (4-4), please see Appendix B. Equation (4-4) is illustrated in Figure 9.

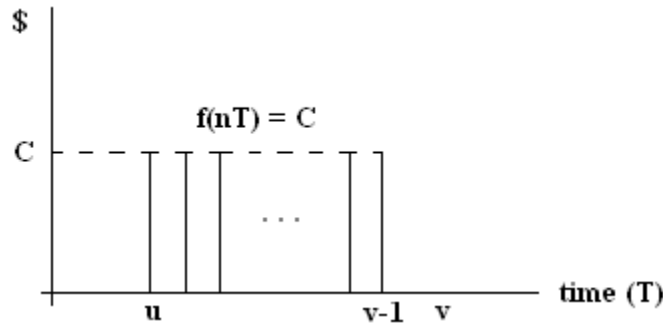


FIGURE 9

On-off Operation for Zeta Transform of a Step Function

Numerical Illustration. We revisit the numerical example of the earlier section where the penalty cost for a future delivery from a supplier, given the historical delivery performance and management data for a delivery window of four days, turned out to be \$135. Let us suppose that this supplier is scheduled to deliver *quarterly* in a year. Then following (4-1), the penalty cost resulting from the four deliveries ($N = 4$) is $\$135 \times 4 = \540 . Clearly, this approach does not consider the present worth of the cost stream associated with the four deliveries. Utilizing the zeta transform defined in equation (4-4) and adopting an appropriate cost of capital will yield a discounted penalty cost of less than \$135 for each future untimely delivery.

4.2.2. A Profile for Improving Untimely Delivery

The consideration of a constant penalty cost of C for each future delivery is a great starting point for model building. However, in reality, it is expected that when the first delivery is made in the third month that leads to the penalty cost C , the supplier will make amendments in order to reduce the penalty cost for the next delivery, i.e., for the delivery in the sixth month, the penalty cost should ideally be less than C , and this trend should continue, making the penalty cost lesser

for each delivery and thereby making the overall supply chain more competitive by continuous improvement. This has been defined in this chapter as “improving” at the supplier’s end.

As stated in the earlier section, the unique properties of a zeta transformation add to its versatility in creating transforms of standard functions like “ramp”, “step”, and “decay”. A zeta transform of a *decay* function is an attractive means for modeling the decrease in expected penalty costs that occur as a result of investing in improvements to delivery performance. The negative exponential form of the improving rate implies that as improvement increases, cost decreases. The zeta transformation for the decay function is given by:

$$TPV (C_N) = \frac{C(1+i)^{(1-b)}}{1+i-e^{-r}} \left\{ \frac{e^{-hr}}{(1+i)^h} - \frac{e^{-kr}}{(1+i)^k} \right\} \quad (4-5)$$

where

N = number of deliveries

b = the point where improvement starts

h = the point where the first cash flow due to improvement occurs, turn on

k-1 = ending point of cash flow (k -1 = N); series is turned off at k

r = improving rate

A complete derivation for equation (4-5) is available in Appendix B. Equation (4-5) is illustrated in Figure 10.

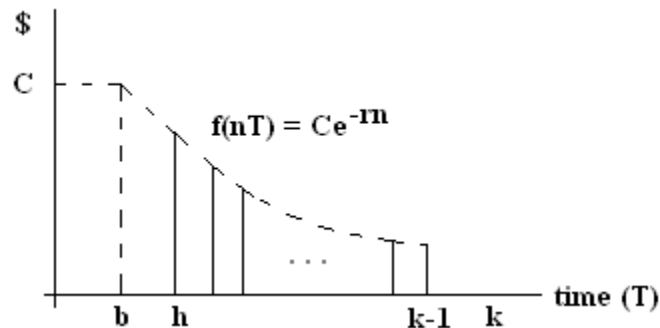


FIGURE 10
On-off Operation for Zeta Transform of a Decay Function

Figure 10 provides an interesting departure from the context of penalty cost considerations in this essay. While there is no cash flow at point ‘b’ of Figure 10, our scenario for supplier deliveries and associated penalty costs are slightly different. We are considering penalty costs from four upcoming deliveries for a year. For the first delivery (i.e., at the end of the first quarter), the penalty cost is C. So this delivery corresponds to point ‘u’ of Figure 9. As improvement begins after the first penalty is affected on the supplier, the penalty cost for delivery in the third month remains C. However, for a reduction in penalty cost to happen in the second delivery (i.e., end of the second quarter) due to improvement, improvement has to begin at the end of the first quarter. Thus the first delivery is also point ‘b’ of Figure 10. This is incorporated by a combination of the step function (from point ‘u’ till the point ‘v-1’) and a decay function (from point ‘b’; in this case, v-1 = b). This set of dynamics is illustrated in Figure 10. Based on the linear operator property of the zeta transform, we can write the complete zeta transform for a combination of the step and decay functions as:

$$\text{TPV}(C_N) = (C/i) [(1+i)^{1-u} - (1+i)^{1-v}] + \frac{C(1+i)^{(1-b)}}{1+i-e^{-r}} \left\{ \frac{e^{-hr}}{(1+i)^h} - \frac{e^{-kr}}{(1+i)^k} \right\} \quad (4-6)$$

Since the points ‘v-1’ and ‘b’ coincide, v = b + 1; thus 1-v = -b. Thus we can re-write (4-6) as

$$\text{TPV}(C_N) = (C/i) [(1+i)^{1-u} - (1+i)^{-b}] + \frac{C(1+i)^{(1-b)}}{1+i-e^{-r}} \left\{ \frac{e^{-hr}}{(1+i)^h} - \frac{e^{-kr}}{(1+i)^k} \right\} \quad (4-7)$$

Equation (4-7) is illustrated in Figure 11.

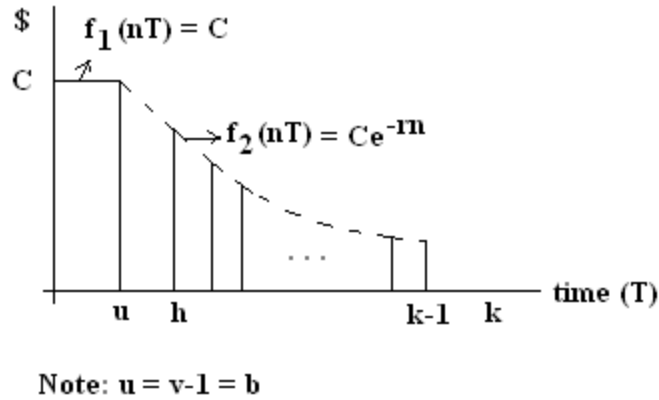


Figure 11

Linear Operator property of Zeta Transform to merge Step and Decay Functions

Returning to our numerical illustration of Section 3.3.3., $C = \$135$; $i = 10\%$ APR, thus 2.5% for quarterly delivery; $u = 1$ (the first cash flow of penalty cost is realized at the first delivery). There is no improvement in the first cash flow. As improvement starts happening after the first penalty is effected on the supplier, the penalty cost for delivery in the third month remains $\$135$; hereafter it reduces based on the improving rate and thus $b = 1$ (when improvement starts), $h = 2$ (when the first cash flow due to improvement occurs), and $k - 1 = 4$ (this is the final cash flow), $k = 5$. Thus, utilizing equation (17), $TPV(C_N) = \$184$, not $\$540$. Figure 12 lists the profiles of penalty costs for improving rates of 25% , 50% , and 75% , respectively.

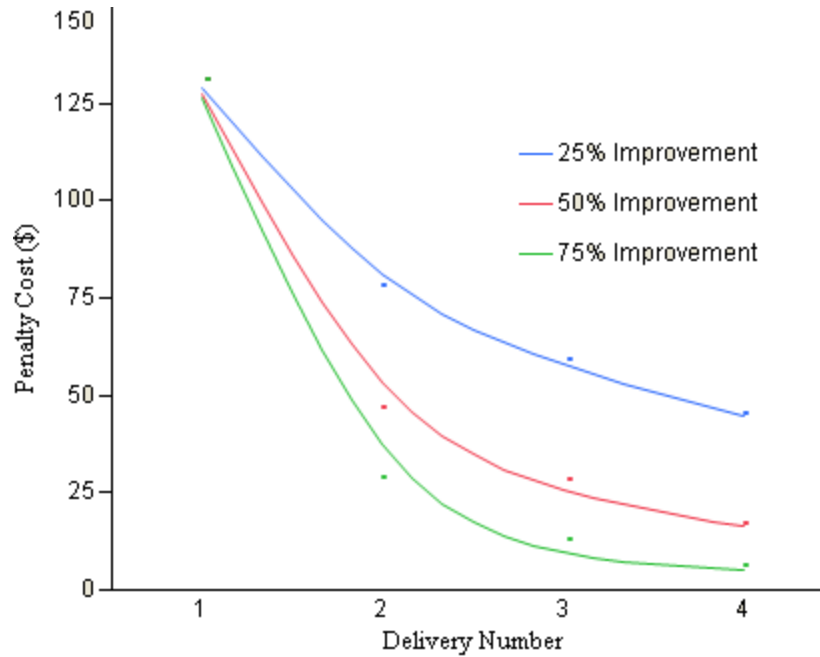


FIGURE 12
Improvement Profiles

4.3. Opportunity Costs of Delaying Improvement in Penalty costs

This section discusses the financial implications of failing to consider improvements in penalty cost analysis due to untimely deliveries. The on-off operator of the zeta transform is key to modeling the implications of *buyer neglect*. Guided by previous work on managerial neglect by Guiffrida and Nagi (2006b), we define buyer neglect as *the opportunity cost of buyer management's failure to introduce improvement in supplier delivery performance in proper time*. The consequences of buyer neglect on supply chain operations can be critical. The failure to measure supplier delivery performance in accurate financial terms may impede the capital budgeting process, which is necessary to support supplier operations within a supply chain.

We start the discussion on buyer neglect by re-visiting equation (4-7), the total present value of the expected penalty cost for N future deliveries, such that the first delivery occurs at point

‘u’, the improvement begins at point ‘b’, the first cash flow due to improvement begins at point ‘h’, and the cash flow is turned off at point k, as shown below:

$$\text{TPV } (C_N) = (C/i) [(1+i)^{1-u} - (1+i)^{-b}] + \frac{C(1+i)^{(1-b)}}{1+i-e^{-r}} \left\{ \frac{e^{-hr}}{(1+i)^h} - \frac{e^{-kr}}{(1+i)^k} \right\} \quad (4-8)$$

We have contended previously that there is no improvement for the penalty cost due to the first delivery. Clearly, when the first cash flow begins on the first delivery at point ‘u’, and when improvement starts from that point, then there is no buyer neglect, i.e., $b = u$ is the ideal case in equation (4-8) when there is no buyer neglect. At the same time, the first cash flow due to improvement begins in the next period, i.e., $h = b + 1 = u + 1$. Thus the case for *no buyer neglect* can be written mathematically as follows:

$$\text{TPV } (C_N) = (C/i) [(1+i)^{1-u} - (1+i)^{-u}] + \frac{C(1+i)^{(1-u)}}{1+i-e^{-r}} \left\{ \frac{e^{-(u+1)r}}{(1+i)^{u+1}} - \frac{e^{-kr}}{(1+i)^k} \right\} \quad (4-9)$$

Buyer neglect begins when the consideration for improvement does not begin with the first delivery, i.e., $b > u$. Thus for $b = w$ (where $w > u$), $h = w + 1$ (since the cash flow due to improvement happens in the period following the period where the consideration for improvement is made). The associated total present value of the expected penalty costs is

$$\text{TPV } (C_N) = (C/i) [(1+i)^{1-u} - (1+i)^{-w}] + \frac{C(1+i)^{(1-w)}}{1+i-e^{-r}} \left\{ \frac{e^{-(w+1)r}}{(1+i)^{w+1}} - \frac{e^{-kr}}{(1+i)^k} \right\} \quad (4-10)$$

Subtracting (4-9) from (4-10) yields total present value of opportunity cost due to neglect as

$$\begin{aligned} & \frac{C}{i} \left\{ \frac{1}{(1+i)^u} - \frac{1}{(1+i)^w} \right\} + \frac{C e^{-kr}}{1+i-e^{-r}} \{ (1+i)^{1-u-k} - (1+i)^{1-w-k} \} \\ & + \frac{C e^{-r}}{1+i-e^{-r}} \left\{ \frac{(1+i)^{-2w}}{e^{wr}} - \frac{(1+i)^{-2u}}{e^{ur}} \right\} \end{aligned} \quad (4-11)$$

where C = expected penalty cost of with a delivery

i = interest rate associated with constant length time interval between deliveries

u = starting point of cash flow; turn on for step series

w = point where improvement starts; turn off for step series

Equation (4-11) represents the opportunity cost due to managerial neglect. This opportunity cost due to buyer neglect in considering improvement at point 'w' instead of point 'u' is illustrated in Figure 13.

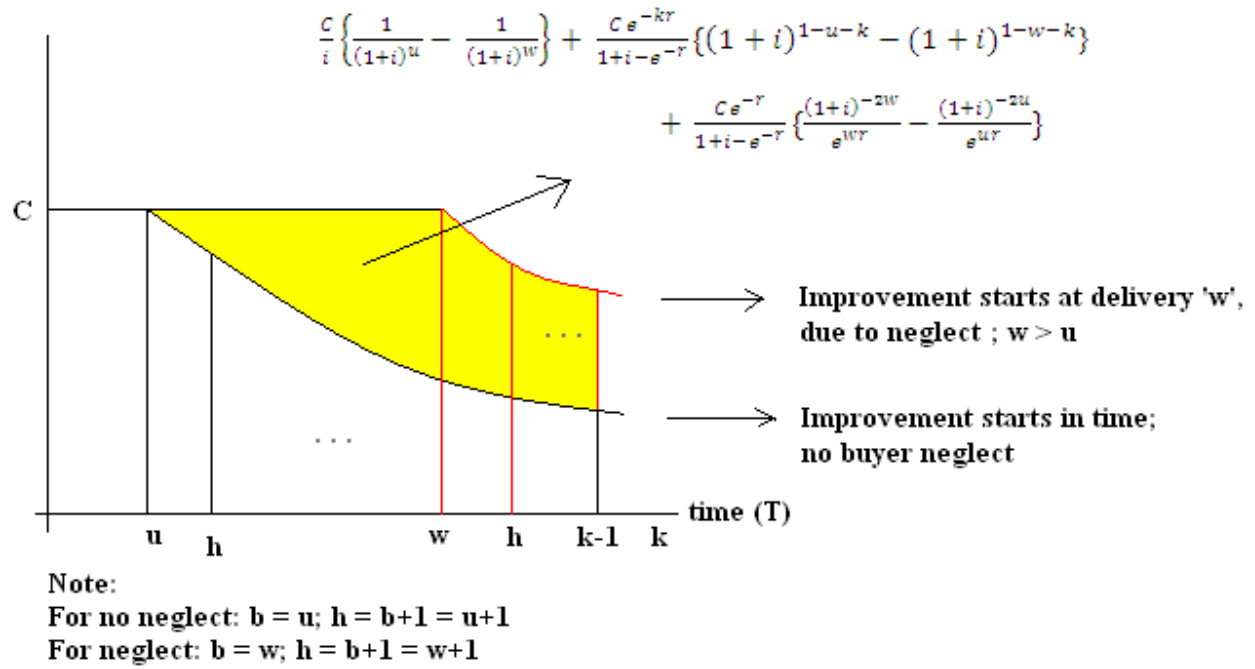


FIGURE 13
On-Off Operation in Zeta Transform for Buyer Neglect

We observe:

- As ' r ' *increases*, the total present value of the opportunity cost of neglect also *increases*.
- As ' w ' *increases*, the total present value of the opportunity cost of neglect also *increases*.

Numerical Illustration 1. We used the on-off operator in the earlier section to understand the total present value of penalty costs when improvement starts at the first delivery (i.e., $b=1$) and the first cash flow due to improvement is realized in the subsequent delivery (i.e., $h = 2$). The total present value for $C = \$135$ turned out to be \$184. If realization of improvement is delayed by another period (i.e. in the second delivery such that $b = 2$ and $h = 3$), the total present value increases to \$281. The difference, i.e. \$97 is attributed to managerial neglect of one period.

Numerical Illustration 2. While the financial implications of buyer neglect are clearly parameter dependent (for example, the improvement rate ' r '), a macro-level view of the financial implications over time may serve as a useful input into the managerial decision making process for implementing a continuous improvement program to improve supplier delivery performance.

Let us assume that a supplier is slated to deliver six times in a year (i.e., $k = 7$) and that the expected penalty cost of a delivery, i.e. $C = 135$ (from our previous section). Also the cost of capital is a 10% APR, i.e. the interest rate for each delivery period is about 0.017. When improvement is captured at the first delivery, i.e., at $b = 1$, then there is no neglect. Thus the financial loss due to neglect for $b = 1$ is zero. If consideration of improvement is neglected for one delivery and started at the next, i.e., at $b = 2$, then the opportunity cost due to late consideration of improvement by one delivery is captured by the financial impact due to buyer neglect in Table 5. Table 5 provides financial impacts due to managerial neglect for different profiles of neglect periods and different profiles of improvement rates. Following Table 5, Figure 14 provides a graphical comparison of buyer neglect for different parameter profiles.

Length of Neglect	Improvement Rate			
	0.25	0.45	0.65	0.85
0; No Buyer Neglect (b = 1; h = 2)	\$0	\$0	\$0	\$0
1 (b = 2; h = 3)	\$49	\$77	\$95	\$106
2 (b = 3; h = 4)	\$117	\$173	\$205	\$225
3 (b = 4; h = 5)	\$198	\$279	\$323	\$347
4 (b = 5; h = 6)	\$289	\$390	\$442	\$470

TABLE 5
Financial Impact of Buyer Neglect for Different Parameter Profiles

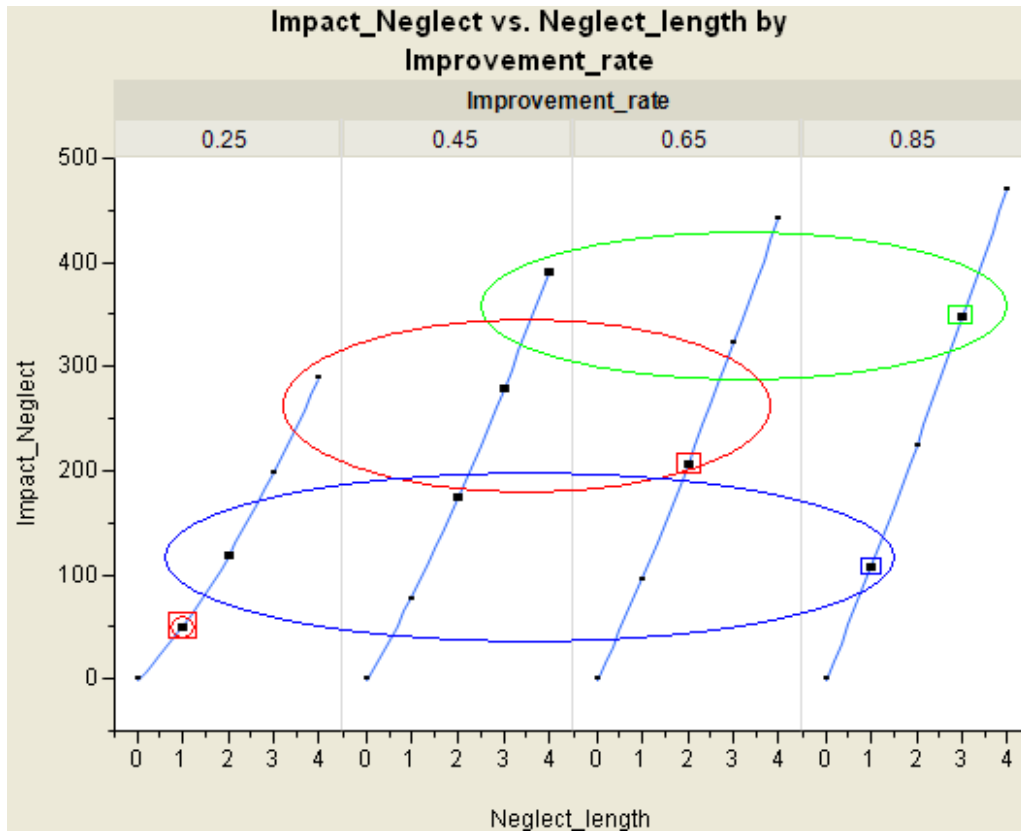


FIGURE 14
Comparison of Buyer Neglect for different parameter profiles

Examining Table 5, the minimum impact of buyer neglect occurs when there is no neglect and when the supplier improvement rate is very low. An interaction effect is visible between the length of neglect and the supplier's improvement rate. As an example, a buyer is better off with failing to consider improvement in three deliveries from a supplier with a higher improvement rate as opposed to the same in four deliveries from a supplier with a lower improvement rate.

4.4. The Price of Improvement

An important feature in the discussion of buyer neglect in the previous section is 'improvement'. Since the opportunity cost due to buyer neglect was measured by looking at the period when improvement commences; improvement, in the scheme of our study is imposed by the buyer. Thus, improvement comes at a price. Let us assume that the price of improvement is given by C^* . From our discussion in Section 4.2.2., we contend that when the consideration of improvement is made at point 'w', the first cash flow due to improvement occurs at point 'h', where $h = w + 1$. This is also the point where the price for improvement is paid. Since improvement continues until the last delivery, the price for improvement is paid until the point $k-1$. This improvement price, C^* , is a unit step function and can be modeled as an on-off zeta transform for a unit step function (see equation (4-4) and Figure 9). Hence, the total present value of prices paid for improvements, becomes

$$TPV (\text{Price of Investment}) = (C^*/i) [(1+i)^{-w} - (1+i)^{1-k}] \quad (4-12)$$

However, we acknowledge that improvement at the supplier's end is a requirement for continuous improvement; thus a higher improvement rate of a supplier should be rewarded by easing the price paid by the buyer for improvement. This reasoning is reflected in our modeling effort by rewriting (4-12) as

$$\text{TPV (Price of Investment)} = (C^*/ir) [(1+i)^{-w} - (1+i)^{1-k}] \quad (4-13)$$

We observe:

- As 'r' *increases*, the total present value of the price of improvement *decreases*.
- As 'w' *increases*, the total present value of the price of improvement *decreases*.

Numerical Illustration. Let us assume that a supplier is slated to deliver six times in a year (i.e., $k = 7$) and that the price of improvement per delivery, i.e. $C^* = \$67.5$. Also the cost of capital is a 10% APR, i.e. the interest rate for each delivery period is about 0.017. When improvement is captured at the first delivery, i.e., at $w = 1$, then there is no neglect. At the same time, the cash flow due to improvement begins at the next delivery, i.e., at $h = w + 1 = 2$. This is where the buyer starts paying a price C^* for improvement and continues to pay so till the $(k-1)$ delivery. If the buyer fails to capture this improvement in time, then the price due to improvement is also captured for lesser deliveries. Table 6 provides price of improvement for different profiles of neglect periods and different profiles of improvement rates. Following Table 6, Figure 15 provides a graphical comparison of buyer price of improvement for different parameter profiles.

It is interesting to note from Table 6 that while the minimum impact of price paid for improvement is when there is maximum neglect (due to delayed payment for improvement) coupled to a high supplier improvement rate, there is again a visible interaction effect between the length of neglect and the supplier's improvement rate. As an example, a buyer is better off capturing improvement early for a supplier with a higher improvement rate as opposed to capturing improvement late for a supplier with lower improvement rate.

Length of Neglect	Improvement Rate			
	0.25	0.45	0.65	0.85
0; No Buyer Neglect (w = 1)	\$1262	\$701	\$486	\$371
1 (w = 2)	\$1001	\$556	\$385	\$294
2 (w = 3)	\$745	\$414	\$286	\$219
3 (w = 4)	\$492	\$273	\$189	\$145
4 (w = 5)	\$244	\$136	\$94	\$72

TABLE 6
Price of Improvement for Different Parameter Profiles

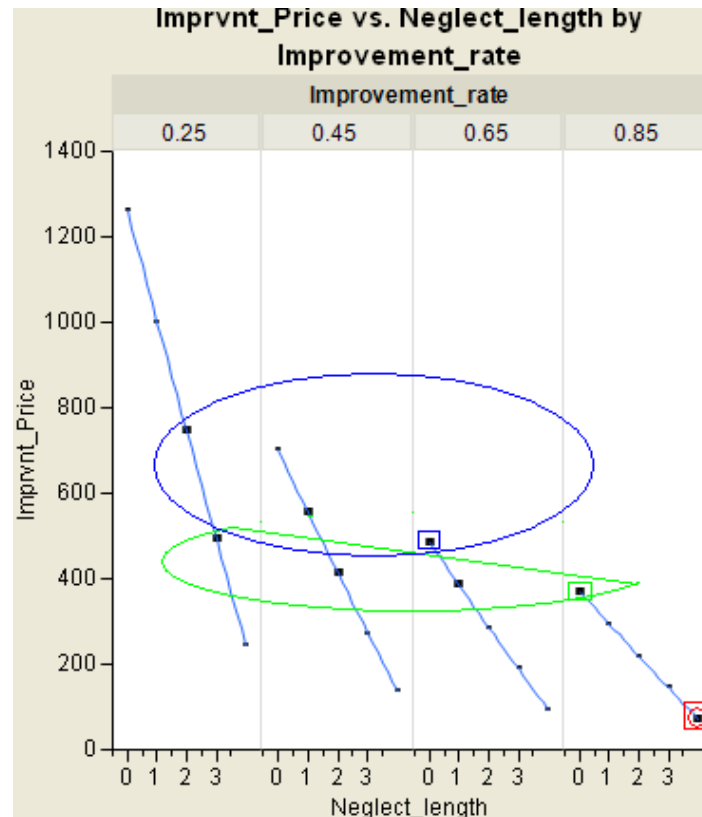


FIGURE 15
Comparison of Price of Improvement for different parameter profiles

4.5. An Optimized Buyer Spending Model for Supplier Improvement

Combining the numerical illustrations from Tables 4 and 5, we get a comprehensive picture of buyer spending for supplier improvement in different parameter profiles as showcased in Table 7.

Length of Neglect	Improvement Rate			
	0.25	0.45	0.65	0.85
0; No Buyer Neglect (w = 1)	\$1262	\$701	\$486	\$371
1 (w = 2)	\$1050	\$633	\$480	400
2 (w = 3)	\$862	\$587	\$491	\$444
3 (w = 4)	\$690	\$552	\$512	\$492
4 (w = 5)	\$533	\$526	\$536	\$542

TABLE 7
Total Buyer Spending for Different Parameter Profiles

Table 7 presents an interesting set of dynamics with respect to investing in the CI of delivery performance. While it is clear that minimizing buyer neglect and maximizing supplier improvement rate provides the best return in terms of buyer spending, the situation can get very complex with pre-determined buyer expectations. As an example, if the total buyer spending has a cap of \$550, and the buyer does not expect the supplier to operate at more than 80% improvement rate, while not considering any supplier with an improvement rate of less than 50%, then minimizing buyer neglect is not the best option, as a buyer neglect of one delivery for

a supplier with improvement rate of 65% provides the best return (buyer spending = \$480). If the buyer further restricts the expectations of improvement rate as between 40% and 60%, then the best return shifts to a scenario with four deliveries of neglect with a supplier improvement rate of 45% (buyer spending = \$526). Conversely, if the buyer governance makes the decision to invest at least \$500 into supplier delivery improvement, then the best return is a scenario with three deliveries of neglect with a supplier improvement rate of 65% (buyer spending = \$512). Thus different configurations of buyer governance and supplier capabilities lead to different “sweet spots” for the time of consideration of improvement as well as supplier improvement rates. We thus propose a general optimization model to minimize buyer spending for supplier improvement in light of both the supplier improvement rate as well as the time when improvement is captured by the buyer. This general model is then customized for different cases (based on buyer governance and supplier capabilities) to illustrate the utilization of the model.

Let $OCN(r, w)$ = opportunity cost of neglect as a function of ‘r’ and ‘w’ (from Section 4.3)

$$\begin{aligned} \text{Where } OCN(r, w) = & \frac{C}{i} \left\{ \frac{1}{(1+i)^u} - \frac{1}{(1+i)^w} \right\} + \frac{C e^{-kr}}{1+i-e^{-r}} \{ (1+i)^{1-u-k} - (1+i)^{1-w-k} \} \\ & + \frac{C e^{-r}}{1+i-e^{-r}} \left\{ \frac{(1+i)^{-2w}}{e^{wr}} - \frac{(1+i)^{-2u}}{e^{ur}} \right\} \end{aligned} \quad (4-14)$$

Let $PI(r, w)$ = price for improvement as a function of ‘r’ and ‘w’ (from Section 4.4)

$$\text{Where } PI(r, w) = (C^*/ir) [(1+i)^{-w} - (1+i)^{1-k}] \quad (4-15)$$

Then $BSI(r, w)$ = buyer spending for improvement as a function of ‘r’ and ‘w’

$$= OCN(r, w) + PI(r, w)$$

- If r increases, $OCN(r, w)$ increases but $PI(r, w)$ decreases.

- If w increases, $OCN(r, w)$ increases but $PI(r, w)$ decreases.

We thus define our optimization model as follows:

$$\text{Minimize } BSI(r, w) = OCN(r, w) + PI(r, w) \quad (4-16)$$

$$\text{s.t.} \quad u \leq w < N \quad (4-17)$$

$$x_1 < r < x_2 \quad (4-18)$$

$$y_1 \leq BSI(r, w) \leq y_2 \quad (4-19)$$

where $u = 1$

y_1, y_2 = Budget range for Improvement (set by buyer management)

x_1, x_2 = Supplier expected capabilities (set by buyer management)

N = Total number of deliveries

$k - 1 = N$;

I = Cost of Money (on an Annual Percentage Rate); then $i = I/N$

We perform the non-linear optimization using the LINGO software. All software outputs for the numerical illustrations below are provided in Appendix D.

Numerical Illustration: Let us again assume that a supplier is slated to deliver six times in a year (i.e., $k = 7$) and that the penalty cost due to an untimely delivery is $C = \$135$; the price of improvement per delivery, i.e. $C^* = \$67.5$. Also the cost of capital is a 10% APR, i.e. the interest rate for each delivery period is about 0.017.

Case 1: No continuous improvement. The first case is essentially an instantiation of Table 6 with no constraints on the budget or on the supplier improvement rate. Putting in the same limits in the model as shown in Table 6, the objective function returns a value of \$371 for buyer spending, for no buyer neglect and for a supplier improvement rate of 85%, which is in accordance with the outcome in Table 6. This case also serves as a cross-check of the correct model formulation in the software. In reality, this scenario does not conform to continuous improvement at either the buyer's or the supplier's end. The buyer is not obligated to spend towards supplier improvement; nor is the supplier obligated to improve. Therefore, the algorithm remains greedy for both minimum neglect and maximum supplier improvement rate.

Case 2: Continuous improvement at the supplier's end only. The buyer believes that a supplier improvement rate of more than 80% is not realistic. Further, the buyer is not willing to include suppliers with less than 50% improvement rate in its supply base. Thus, while continuous improvement at the supplier's end is accounted for in this scenario, the buyer is still not obligated to spend for improvement. Thus the algorithm still remains greedy for minimum buyer neglect. The buyer investment would be \$394, with maximum supplier improvement rate (within the defined range) and minimum neglect ($w = 1$) from the buyer's end. This scenario is detrimental to the supply chain responsiveness, with no initiative at the buyer's side to improve delivery performance, which can only increase costs in the supply chain (and to the end-customer) by increasing the delivery lead time.

Case 3: Continuous improvement at the buyer's end only. Let us enforce buyer spending for improvement where the minimum spending at the buyer's end is \$400. The supplier improvement is not enforced here, i.e. the buyer maintains a supply base where the supplier improvement rate can be anywhere from 0 through 1. Once again, the algorithm is greedy

towards higher supplier improvement rate. The objective function returns a value of \$400, for no buyer neglect and a supplier improvement rate of 78.8%.

Case 4: Continuous improvement at both the buyer and supplier. In this scenario, we enforce buyer spending for supplier improvement where spending at the buyer's end is a minimum of \$400 and is not to exceed \$500, therefore accounting for continuous improvement of the buyer. The buyer believes that a supplier improvement rate of more than 80% is not realistic. Further, the buyer is not willing to include suppliers with less than 50% improvement rate in its supply base, therefore accounting for continuous improvement at the supplier's end. Now the algorithm is not greedy any more, and seeks for the true optimum value of the objective function. The objective function returns a value of \$400, for a buyer neglect of one delivery and the highest supplier improvement rate (in the defined range). However, if the supplier improvement rate is not restricted to 80%, then the solver returns an objective value of \$400, for no buyer neglect and supplier improvement rate of 78.8%. Thus, for constraints on both the buyer and supplier, the solver seeks the minimum value of the objective function by balancing the length of neglect and the supplier's improvement rate.

Implications of these cases are discussed in the next section.

4.6. Discussion and Implications

The optimization model in this essay is useful in justifying the financial investment required for implementing changes to the existing supply base to reduce the risk of untimely delivery, thereby providing rich implications to both theory and practice.

First, this paper demonstrates the advantage of using zeta transforms in realizing time value of money for discrete cash flows and future modeling. Scalability, forward translation, and

switching properties of the zeta transforms, coupled to supplementary techniques helps in realizing transforms of a wide variety of time series representing cash flow streams of considerable complexity. An instantiation of the zeta transform of complex time series in this paper is the discounted penalty cost function for supplier learning, which is portrayed as an exponential decay function in the earlier section. The zeta transforms are decomposable into standard functions (step ramp, decay, and growth) which recur as sums and products of individual coefficients of the cash flow time series. When these parameters are viewed as random variables (as an example, X_j , the delivery deviation in this paper) with known probability (density) functions, then various statistical moments of these standard forms may be found. Thus use of zeta transforms for penalty cost due to delivery deviation can ultimately lead to variance reduction techniques in delivery deviation.

Second, by incorporating continuous improvement into the model, the essay highlights the opportunity cost of buyer management's failure to measure improvement in delivery performance, thereby demonstrating the detrimental financial effects of buyer neglect.

Third, our model analyzes buyer spending for delivery performance improvement by taking into consideration the opportunity cost of buyer neglect to improvement as well as the price paid for improvement. In optimizing the spending for improvement, we address both supplier capability and supplier management by not only optimizing containment of buyer spending for improvement due to optimum supplier capability, but also using the buyer spending function to address supplier management under a constrained budget for continuous improvement.

Fourth and finally, the numerical analyses conducted using the optimization model developed herein leads to interesting results which are summarized in Table 8.

Scenario	Model Behavior	Application to Practice
No improvement at the supplier's or buyer's end	Greedy algorithm; will always find optimum solution for minimum buyer neglect and maximum supplier improvement rate	Not applicable; lack of improvement from supplier and buyer increases costs in the supply chain; unacceptable
Improvement at the buyer's end only	Greedy algorithm; will find optimum solution for high supplier improvement rate	<ul style="list-style-type: none"> - Increases total penalty cost for untimely deliveries; translates costs to the end-user in the supply chain; not feasible - Calculates the requisite improvement rate of supplier for a defined level of buyer investment; can be used for supplier selection under such specific conditions
Improvement at the supplier's end only	Greedy algorithm; will find optimum solution for minimum buyer neglect	Increases delivery lead-time, therefore reducing responsiveness and agility in the supply chain; unacceptable
Improvement at both the buyer's and supplier's end	Optimum point balances length of neglect with supplier improvement rate	For a defined level of buyer investment, the optimum length of neglect and supplier improvement rate can be determined, without sacrificing continuous improvement of either supplier or buyer

TABLE 8
Modeling Scenarios with Optimized Buyer Spending

4.6.1. Summary Conclusion

This essay uses an optimization model to link the penalty costs associated with untimely delivery and the investment to improve delivery performance to the critical decision outcomes of value sourcing: supplier selection and management. In this final essay, we present a framework for optimizing buyer spending for improvement in supplier delivery performance subject to a prescribed budget constraint. When implemented, we argue that this optimization framework will be an effective decision tool in the management of supplier capability, buyer-supplier alignment, and supplier management. The mathematical model optimized in this essay provides a decision analysis tool for management to address long held concerns in managing supplier

capability. The modeling effort presented herein is proactive and directly supports long-term continuous improvement initiative in the supply base, which is supportive of modern day global supply management.

The following chapter concluded this dissertation with an executive summary and directions for future research.

CHAPTER 5

SUMMARY AND FUTURE RESEARCH DIRECTIONS

5.1. Supply Chain Perspectives on Value Sourcing and Delivery Performance

This dissertation, in the form of three essays, contributes to a comprehensive understanding of value sourcing practices in supply chain management.

In the first essay, a value sourcing framework was presented. The design and sourcing implementation strategies illustrated in the framework present an attractive methodology for adding value in a supply chain. The value sourcing framework conceptualized in this essay utilizes two core phases of managerial decision making:

Phase I: Realization of cost from performance measures, and

Phase II: Decision making from cost analysis.

The value sourcing framework developed in the first essay maps supplier performance to buyer cost, therefore supporting supplier evaluation and selection. Further, in mapping cost to decision making, the framework also addresses supplier development, therefore integrating continuous improvement to both theory and practice of supply chain management.

The second essay illustrates the first phase of managerial decision making, i.e., realization of cost from performance measures, by linking supplier delivery performance to the value sourcing initiative of supplier evaluation. Costs associated with untimely delivery and investments are minimized to improve delivery performance and a penalty cost model for untimely delivery is designed to enhanced buyer-supplier alignment in the supply chain. Such a penalty cost model

for untimely delivery that quantifies supplier delivery performance in metrics (probability and cost) is of importance to researchers and practitioners, alike.

Finally, the third essay illustrates the second phase of managerial decision making, i.e., decision making from cost analysis. The penalty cost model for untimely delivery that was designed in Essay 2 is utilized to optimize a buyer's investment in the improvement of supplier delivery performance. Guided by a prescribed budget constraint for continuous improvement, this essay optimizes the buyer spending for improvement in supplier delivery performance to gauge supplier capability as well as supplier management.

5.2. Directions for Future Research

This dissertation paves the way to several future directions in both theory and practice.

First, the value sourcing framework developed in this dissertation incorporates environmental sustainability as an integral value attribute for supply chains. The inclusion of environmental sustainability in the list of value attributes for best value supply chains offers an interesting mix. As supply chains juggle between 'short term' cost containment using agile measures and 'long-term' cost containment using environmentally sustainable measures, sourcing initiatives move across a continuum in different degrees, begging an investigation on their role in optimizing supply chain performance. It would only be in the realm of conjecture to extrapolate from our framework and future research might find this study a stepping stone for seeking answers in the same genre.

Second, studies that are focused on empirically testing the nature of the hierarchical and lateral relationships between the four value attributes as proposed in Essay 1 of this dissertation should be undertaken. Within this context, research could be conducted to understand the nature of tradeoffs that may exist between the choices of value attributes. For example, are supply

chains (or organizations within a supply chain) more likely to favor and promote one type of value attribute (e.g. agility) over the others? Is there synergy between some of the attributes? As an example, on face value, it seems that an adaptive and aligned supply chain is also agile. Further empirical testing will solidify the nature of relationship between these value attributes, whether they are strong, moderate, or weak. Finally, researchers and practitioners will gain from a comprehensive understanding of the degree of each of these value attributes the recipe for a sufficient building block towards attaining competitive priorities.

Third, while the penalty cost model introduced in Essay 2 has been illustrated numerically to understand supplier selection strategies, we used discrete probability distributions to develop the expected penalty cost for a future untimely delivery. This penalty cost model has also been used in Essay 3 to define the buyer investment for improvement in supplier delivery performance. Thus, the stochastic nature of the variables like supply risk, delivery window, supplier improvement rate, etc. have not been considered in this dissertation. The stochastic impact of variables in these models may lead to an enhanced understanding of delivery performance in a supply chain.

Fourth, while Essay 2 designs a penalty cost model for future untimely supplier delivery that differentiates between early and late deliveries in both frequency and magnitude, the risk parameter β used in the model opens up opportunity towards future research. In light of the current volatile global business environment and growing environmental concerns over global warming and carbon footprints, this paper proposes that management look at both supply risk considerations as well as a supplier's alliance to environmental sustainability to define the risk parameter, β . Future research and practice might find this model as a starting point for a green, risk adjusted delivery performance model.

Fifth and finally, while this dissertation introduces an improvement rate “ r ” in Essay 3, the characteristics of the improvement rate “ r ” and those of the risk factor β hint at a possible link between these two variables, which has not been addressed in this dissertation. Future research will strive to streamline buyer spending decisions in the light of supply risk, where supply risks drive the improvement rate of a supplier, i.e. “ r ” can possibly be defined as a function of β leading to variable reduction, therefore enhancing analysis time.

APPENDIX A
NOTATIONS AND SYMBOLS USED

CDMA	Code Division Multiple Access
CI	Continuous Improvement
CS	Customer Service
DCF	Discounted Cash Flow
PSM	Purchasing and Supply Management
QM	Quality Management
QLF	Quality Loss Function
SCM	Supply Chain Management
OM	Operations Management
SSCM	Strategic Supply Chain Management
VS	Value Sourcing
MLE	Maximum Likelihood Estimator

Mathematical Notations

C_{early}	Penalty cost component of an early delivery
C_{late}	Penalty cost component of a late delivery
m	A proportionality constant depending on the buyer's penalty cost structure
C	Expected penalty cost incurred for a future delivery
N	The number of deliveries to be made annually
k	Number of delivery deviations

j	A count of the delivery deviations; $j = 1, 2, 3 \dots k$
X_j	The magnitude of the j -th delivery deviation
n_j	Frequency of X_j
\hat{p}_j	The MLE for the probability of the j^{th} delivery deviation
DW	Delivery Window
X^+	A function; $\text{Max}(X, 0)$
X^-	A function; $\text{Min}(X, 0)$
β	A parameter ($0 < \beta \leq 1$) of <i>flexibility</i> assigned by the buyer
C_1	Inventory holding cost per unit time of an early delivery
C_2	Penalty cost per unit time of a late delivery
TPV	Total Present Value
T	Constant length time interval
i	Interest rate associated with interest conversion time period T
u	The point where cash flow starts; step series turns ON
$v-1$	Final point of cash flow for the step function; step series turns OFF at v
b	The point where improvement starts
h	Starting point of cash flow due to improvement; decay series turns ON
$k-1$	Final point of cash flow due to improvement; decay series turns OFF at k
r	Improvement rate

APPENDIX B

DERIVATIONS IN SUPPORT OF CHAPTER 4 (Essay 3)

B1. Zeta Transformations for Uniform and Decaying Cash Flow Time Series

Let $f(nT)$ define a discrete cash flow time series where n is the number of compounding periods and T is the constant-length time interval between periods. For a cash flow time series of infinite length where interest is compounded per period at rate i , Hill and Buck (1974) define the zeta transform of this series as

$$z\{f(nT)\} = \sum_{n=0}^{\infty} f(nT)(1-iT)^{-n}. \quad (\text{B-1})$$

For a uniform discrete cash flow series where $f(nT) = c$ we note that for $w = 1/(1+iT)$, (B-1) takes the general form the geometric series $c \sum_{n=0}^{\infty} w^n$ which for $n \rightarrow \infty$ converges to $\frac{c}{1-w}$ provided that $|w| < 1$. Applying this result to (B-1) yields

$$\begin{aligned} z\{f(nT)\} &= \frac{c}{1 - \frac{1}{1+iT}} \\ &= \frac{c}{\frac{iT}{1+iT}} \\ &= \frac{c(1+iT)}{iT} \end{aligned} \quad (\text{B-2})$$

which is reported in Hill and Buck (1974, p. 121) as the present value of the discrete uniform cash flow time series $f(nT) = c$ for a time horizon starting at $n = 0$ and ending at $n = \infty$.

Let $f(nT) = ce^{-rnT}$ define a decaying discrete cash flow time series with decay rate r . Applying (B-1), the zeta transform of this time series is

$$\begin{aligned}
 z\{f(nT)\} &= \sum_{n=0}^{\infty} (ce^{-rnT})(1-iT)^{-n} \\
 &= c \sum_{n=0}^{\infty} (1+iT)^{-n} (e^{rt})^{-n} \\
 &= c \sum_{n=0}^{\infty} \left[(1+iT)^{-1} (1+iT)^{-1} \right]^n.
 \end{aligned} \tag{B-3}$$

Adopting the convergence argument used in the derivation of (B-2), the zeta transformation of a decaying discrete cash flow time series is

$$\begin{aligned}
 z\{f(nT)\} &= \frac{c}{1 - \frac{1}{(1+iT)e^{rt}}} \\
 &= \frac{c(1+iT)}{iT + 1 - e^{-rt}}
 \end{aligned} \tag{B-4}$$

which is reported in Hill and Buck (1974, p. 121) as the present value of the discrete decaying cash flow time series $f(nT) = ce^{-rnT}$ for a time horizon starting at $n = 0$ and ending at $n = \infty$.

B2. Zeta Transformation for Uniform and Decaying Cash flow using the On-Off Operator

The present value of the discrete uniform cash flow time series $f(nT) = c$ for a time horizon starting at $n = 0$ and ending at $n = \infty$ is given in equation (B-2). Let us consider a similar function $g(nT)$ that triggers at point 'h' and stops at point 'k'. Then, for the triggering point 'h', the time series is given by:

$$g(nT) = \begin{cases} 0 & \text{if } nT < h \\ f(nT - h) & \text{if } nT \geq h \end{cases} \quad (\text{B-5})$$

Applying (B-1), the zeta transform of this time series is

$$\begin{aligned} z \{ g(nT) \} &= \sum_{n=0}^{\infty} g(nT)(1 + iT)^{-n} \\ &= \sum_{n=h/T}^{\infty} f(nT - h)(1 + iT)^{-n} \end{aligned} \quad (\text{B-6})$$

The lower bound for $(nT - h)$ is 0; thus $n = h/T$ for the lower bound in (B-6).

To express the lower bound in the same form as in (B-1), let $n^* = n - h/T$. Thus when $n \rightarrow h/T$; $n^* \rightarrow 0$. We now re-write (B-6) as follows:

$$\begin{aligned} z \{ g(nT) \} &= \sum_{n^*=0}^{\infty} f(n^*T)(1 + iT)^{-(n^* + \frac{h}{T})} \\ &= (1+iT)^{-h/T} \sum_{n^*=0}^{\infty} f(n^*T)(1 + iT)^{-n^*} \end{aligned}$$

Applying (B-1),

$$z \{ g(nT) \} = (1+iT)^{-h/T} z \{ f(n^*T) \}$$

Applying (B-2)

$$z \{ g(nT) \} = (1+iT)^{-h/T} z \{ C \} = (1+iT)^{-h/T} C \left(\frac{1+iT}{iT} \right) \quad (\text{B-7})$$

$$\text{For } T = 1, (\text{B-7}) \text{ can now be rewritten as: } \left(\frac{C}{i} \right) (1 + i)^{1-h} \quad (\text{B-8})$$

Adopting (B-7), the zeta transformation for a decay function that triggers at point ‘k’ and ends at ∞ , we have:

$$z \{ g(nT) \} = (1+iT)^{-k/T} z \{ C \} = (1+iT)^{-k/T} C \left(\frac{1+iT}{iT} \right) \quad (B-9)$$

For $T=1$, (B-9) becomes

$$z \{ g(nT) \} = \left(\frac{C}{i} \right) (1+i)^{1-k} \quad (B-10)$$

Thus if the function starts at ‘h’ and stops at ‘k’, by combining equations (B-8) and (B-10), we can express the present value of the discrete uniform cash flow time series $f(nT) = c$ for a time horizon starting at $n = 0$ and ending at $n = \infty$. by using the on-off operator in zeta transformation as

$$z \{ C \} = \left(\frac{C}{i} \right) \{ (1+i)^{1-h} - (1+i)^{1-k} \} \quad (B-11)$$

Applying the on-off operator property of a zeta transform to a decaying discrete cash flow time series $f(nT) = ce^{-rnT}$ with decay rate r yields similar transformations. Thus for a decaying time series, we may re-write B-7 as

$$(1+iT)^{-\{(b/T) + (h/T)\}} z \{ C \} = [(1+iT)^{-\{(b/T) + (h/T)\}}] C \left(\frac{1+iT}{iT+1-e^{-rT}} \right) e^{-hrT} \quad (B-12)$$

where ‘h’ and ‘k’ are the on and off operators respectively, and ‘b’ is the point where decay starts getting realized.

For $T = 1$, (B-12) may be re-written as:

$$\frac{C (1+i)^{1-b}}{1+i-e^{-r}} \left(\frac{e^{-hr}}{(1+i)^h} \right) \quad (B-13)$$

Adopting (B-13), the zeta transformation for a decay function that triggers at point ‘k’ and ends at ∞ , we have:

$$\frac{C (1+i)^{1-b}}{1+i-e^{-r}} \left(\frac{e^{-kr}}{(1+i)^k} \right) \quad (\text{B-14})$$

Thus if the function starts at ‘h’ and stops at ‘k’, by combining equations (B-13) and (B-14), we can express the present value of the discrete decay cash flow time series $f(nT) = ce^{-rnT}$ for a time horizon starting at $n = 0$ and ending at $n = \infty$ by using the on-off operator in zeta transformation as

$$z\{C\} = \frac{C (1+i)^{1-b}}{1+i-e^{-r}} \left\{ \left(\frac{e^{-hr}}{(1+i)^h} \right) - \left(\frac{e^{-kr}}{(1+i)^k} \right) \right\} \quad (\text{B-15})$$

APPENDIX C

LINGO CODE FOR OPTIMIZATION MODEL IN CHAPTER 3 (Essay 2)

! Objective;

MIN = $(1/(k*(1+k^2)))*((C1*p*@exp(-delta/(p*k)))+ 2*C2*(delta^2-theta^2)*@exp(-k*delta/p))+ (lambda/@log(1/(1-h)))*(@log(p0)-@log(p));$

!Subject to::

$p \leq p0;$

$p \geq k*delta/2;$

$k \leq .9;$

$k \geq 0.25;$

$delta > 3;$

$delta \leq 14;$

!Data;

$C1 = 100;$

$C2 = 400;$

$theta = 0;$

$p0 = 3;$

$lambda = 20;$

$h = 0.10;$

Global optimal solution found.

Objective value:	756.7591
Objective bound:	756.7591
Infeasibilities:	0.000000
Extended solver steps:	16
Total solver iterations:	1859

Variable	Value	Reduced Cost
K	0.9000000	0.000000
C1	100.0000	0.000000
P	1.350000	0.000000
DELTA	3.000000	0.000000
C2	400.0000	0.000000
THETA	0.000000	0.000000
LAMBDA	20.00000	0.000000
H	0.1000000	0.000000
P0	3.000000	0.000000

APPENDIX D

LINGO CODES FOR OPTIMIZATION MODELS IN CHAPTER 4 (Essay 3)

Case 1:

! Objective;

MIN = (C/i)*(1/((1+i)^u) - (1/((1+i)^w))) + ((c*@EXP(-k*r))/(1+i-@EXP(-r)))*(((1+i)^(1-u-k))-((1+i)^(1-w-k)))
+ ((c*@EXP(-r))/(1+i-@EXP(-r)))*(((1+i)^(-2*w))/(@EXP(w*r))-((1+i)^(-2*u))/(@EXP(u*r))) + (CSTAR/(i*r))*(((1+i)^-w)-(1+i)^(1-k));

!Subject to::

w >= u;

w < N;

r >= 0.25

r <= 0.85;

!Data;

C = 135;

CSTAR = 67.5;

u = 1;

N = 6;

k = 7;

i = 0.017;

BCI = 500;

Yields the following output:

Global optimal solution found.

Objective value: 371.2739

Objective bound: 371.2739

Infeasibilities: 0.000000

Extended solver steps: 10

Total solver iterations: 1758

Variable	Value	Reduced Cost
C	135.0000	0.000000
I	0.1700000E-01	0.000000
U	1.000000	0.000000
W	1.000000	0.000000
K	7.000000	0.000000
R	0.8500000	0.000000
CSTAR	67.50000	0.000000

N 6.000000 0.000000

Case 2:

! Objective;

MIN = (C/i)*(1/((1+i)^u) - (1/((1+i)^w))) + ((c*@EXP(-k*r))/(1+i-@EXP(-r)))*(((1+i)^(1-u-k))-((1+i)^(1-w-k)))
+ ((c*@EXP(-r))/(1+i-@EXP(-r)))*(((1+i)^(-2*w))/(@EXP(w*r))-((1+i)^(-2*u))/(@EXP(u*r))) + (CSTAR/(i*r))*(((1+i)^-w)-(1+i)^(1-k));

!Subject to;

w >= u;

w < N;

r >= 0.5;

r <= 0.8;

!Data;

C = 135;

CSTAR = 67.5;

u = 1;

N = 6;

k = 7;

i = 0.017;

Yields the following output:

Global optimal solution found.

Objective value: 394.4785

Objective bound: 394.4785

Infeasibilities: 0.000000

Extended solver steps: 5

Total solver iterations: 812

Variable	Value	Reduced Cost
C	135.0000	0.000000
I	0.1700000E-01	0.000000
U	1.000000	0.000000
W	1.000000	0.000000
K	7.000000	0.000000
R	0.8000000	0.000000
CSTAR	67.50000	0.000000
N	6.000000	0.000000

Case 3:

! Objective;

$$\begin{aligned} \text{MIN} = & (C/i) * (1/((1+i)^u) - (1/((1+i)^w))) + ((c * @EXP(-k*r))/(1+i-@EXP(-r))) * (((1+i)^{(1-u-k)}) - ((1+i)^{(1-w-k)})) \\ & + ((c * @EXP(-r))/(1+i-@EXP(-r))) * (((1+i)^{(-2*w)})/(@EXP(w*r)) - ((1+i)^{(-2*u)})/(@EXP(u*r))) + (CSTAR/(i*r)) * (((1+i)^{-w}) - (1+i)^{(1-k)}); \end{aligned}$$

!Subject to::

$$w \geq u;$$

$$w < N;$$

$$r > 0;$$

$$r < 1;$$

$$\begin{aligned} & ((C/i) * (1/((1+i)^u) - (1/((1+i)^w))) + ((c * @EXP(-k*r))/(1+i-@EXP(-r))) * (((1+i)^{(1-u-k)}) - ((1+i)^{(1-w-k)})) \\ & + ((c * @EXP(-r))/(1+i-@EXP(-r))) * (((1+i)^{(-2*w)})/(@EXP(w*r)) - ((1+i)^{(-2*u)})/(@EXP(u*r))) + (CSTAR/(i*r)) * (((1+i)^{-w}) - (1+i)^{(1-k)})) \geq 400; \end{aligned}$$

!Data;

$$C = 135;$$

$$\text{CSTAR} = 67.5;$$

$$u = 1;$$

$$N = 6;$$

$$k = 7;$$

$$i = 0.017;$$

Yields the following solution:

Global optimal solution found.

Objective value: 400.0000

Objective bound: 400.0000

Infeasibilities: 0.000000

Extended solver steps: 1

Total solver iterations: 100

Variable	Value	Reduced Cost
C	135.0000	0.000000
I	0.1700000E-01	0.000000
U	1.000000	0.000000
W	1.000000	0.000000
K	7.000000	0.000000
R	0.7889571	0.000000

CSTAR	67.50000	0.000000
N	6.000000	0.000000

Case 4:

! Objective;

MIN = (C/i)*(1/((1+i)^u) - (1/((1+i)^w))) + ((c*@EXP(-k*r))/(1+i-@EXP(-r)))*(((1+i)^(1-u-k))-((1+i)^(1-w-k)))
+ ((c*@EXP(-r))/(1+i-@EXP(-r)))*(((1+i)^(-2*w))/(@EXP(w*r))-((1+i)^(-2*u))/(@EXP(u*r))) + (CSTAR/(i*r))*(((1+i)^-w)-(1+i)^(1-k));

!Subject to::

w >= u;

w < N;

r >= 0.5;

r <= 0.8;

((C/i)*(1/((1+i)^u) - (1/((1+i)^w))) + ((c*@EXP(-k*r))/(1+i-@EXP(-r)))*(((1+i)^(1-u-k))-((1+i)^(1-w-k))))

+ ((c*@EXP(-r))/(1+i-@EXP(-r)))*(((1+i)^(-2*w))/(@EXP(w*r))-((1+i)^(-2*u))/(@EXP(u*r))) + (CSTAR/(i*r))

*(((1+i)^-w)-(1+i)^(1-k))) >= 400;

((C/i)*(1/((1+i)^u) - (1/((1+i)^w))) + ((c*@EXP(-k*r))/(1+i-@EXP(-r)))*(((1+i)^(1-u-k))-((1+i)^(1-w-k))))

+ ((c*@EXP(-r))/(1+i-@EXP(-r)))*(((1+i)^(-2*w))/(@EXP(w*r))-((1+i)^(-2*u))/(@EXP(u*r))) + (CSTAR/(i*r))

*(((1+i)^-w)-(1+i)^(1-k))) <= 500;

!Data;

C = 135;

CSTAR = 67.5;

u = 1;

N = 6;

k = 7;

i = 0.017;

Yields the following output:

Global optimal solution found.

Objective value: 400.0000

Objective bound: 400.0000

Infeasibilities: 0.000000

Extended solver steps: 1

Total solver iterations: 93

Variable	Value	Reduced Cost
C	135.0000	0.000000
I	0.1700000E-01	0.000000
U	1.000000	0.000000
W	2.000000	0.000000
K	7.000000	0.000000
R	0.8000000	0.000000
CSTAR	67.50000	0.000000
N	6.000000	0.000000

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