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Selecting the best supply chain strategy: When is a misalignment of product type and strategy appropriate, how do changes in expected demand impact strategies, and should the strategy of a product change over its life-cycle?

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Abstract

To reduce the total cost of delivering a product to the marketplace, many firms are going beyond the walls of their organization and working with suppliers and customers to implement supply chain management (SCM). Fisher (1997) presented a conceptual model contending that the demand characteristics and supply chain strategy (SCS) of a product should be aligned for SCM to be successful. This dissertation presents an original analytical model of a three echelon supply chain to demonstrate under various supply chain conditions that a “misalignment” between demand characteristics and SCS can result in a lower total supply chain cost.

In addition to Fisher (1997), the literature includes a number of SCS frameworks to assist practitioners with identifying the appropriate SCS. However, none have considered a SCS where the supply side employs an agile strategy and demand side utilizes a lean strategy; which is denoted as an “agilean” SCS. This dissertation considers four possible supply chain strategies (lean, agile, leagile, and agilean) and identifies when each SCS type is most effective at minimizing total supply chain cost.

The demand characteristics of a product typically evolve as a product progresses through its life-cycle. The literature presents two views concerning whether the SCS of a product should evolve as the product progresses through its life-cycle. This dissertation demonstrates that a single SCS employed over the life-cycle of a product is generally a more effective SCS to minimize total supply chain cost over the life-cycle of a product than evolving the product’s SCS as it progresses through its life-cycle.

1. Introduction

The contention that in today's business environment it is the supply chains of firms that compete, not the individual firms themselves, and that it is the end consumer whom ultimately determines the success of a firm's supply chain (Christopher, 1992) was made more than 20 years ago. All indications are that this contention is still accurate today. However, the question for supply chains is, "Which supply chain strategy should be employed for which product, and should the supply chain strategy evolve as the demand characteristics of the product evolve over its life-cycle?" Supply chain management is a managerial concept that encompasses a variety of strategies and those strategies can differ at different levels of the supply chain, such as the leagile supply chain strategy, which by one definition combines a lean and an agile supply chain strategy about a decoupling point. One of the largest challenges a supply chain faces when implementing supply chain management is the selection of the appropriate supply chain strategy (SCS) for a product or a family of products. Fisher (1997) stated that for supply chains to fully realize the benefits of supply chain management (SCM), the supply chain strategy of a product must be aligned with the demand characteristics of that product. Figure 1.1 presents Fisher's general framework for successful alignment of the product type and SCS. This framework is referred to as "Fisher Model" for the remainder of this research.

	Functional Product	Innovative Product
Efficient Supply Chain	Match	Mismatch
Responsive Supply Chain	Mismatch	Match

Figure 1.1: Matching supply chain strategy to product type (Source: Fisher, 1997)

1.1 Alignment

The Fisher Model contends that a functional product requires an efficient supply chain and an innovative product requires a responsive supply chain. The Fisher Model classifies products as functional or innovative based on the demand characteristics of the product. A typical functional product has a long product life cycle (PLC), low contribution margin, few product varieties, low demand uncertainty, few stock-outs, and few units sold at a discount at the end of its PLC. In contrast, an innovative product has a short PLC, high contribution margin, many product varieties, high demand uncertainty, many stock-outs, and many units sold at a discount at the end of its PLC. To assist practitioners with determining a product's type, Fisher (1997) provided guidelines for seven demand characteristics detailed in Table 1.1.

	Product Type	
Demand Characteristics	**Functional**	**Innovative**
Product life cycle	>= 2 years	3 months to 1 year
Contribution margin	5% to 20%	20% to 60%
Product variety	Few	Many
Average forecast error	10%	40% to 100%
Average stockout	1% to 2%	10% to 40%
Quantity sold at discount	0%	10% to 25%
Lead time for made to order	6 months to 1 year	1 day to 2 weeks

Source: Fisher, 1997

Table 1.1: Characteristics of functional and innovative products.

The two supply chain strategies considered in the Fisher Model were "efficient" and "responsive". The primary purpose of an efficient SCS is cost minimization, while the primary purpose of a responsive SCS is the ability to respond quickly to demand changes. Both supply chain strategies sought to minimize lead time; however, in an efficient supply chain lead time reduction improvements should be adopted only if there is no negative impact to total supply chain cost. With a responsive SCS, an aggressive approach towards lead time reduction is taken, even though total supply chain cost may increase. Many researchers have related the efficient SCS and responsive SCS in Fisher (1997) to the manufacturing paradigms of lean and agile respectively (Naylor et al., 1999; Mason-Jones et al., 2000; Childerhouse and Towill, 2000; Christopher and Towill, 2001; Huang et al., 2002; Stratton and Warburton, 2003; Qi et al., 2011). This dissertation classifies the SCS where the primary purpose is cost minimization as a "lean SCS" and classifies the SCS where the primary purpose is responsiveness as an "agile SCS". In addition to the primary purpose and lead time focus of the two supply chain strategies, Fisher (1997) described the characteristics of an efficient SCS and a responsive SCS in terms of manufacturing focus, inventory strategy, supplier selection, and product design strategy, as presented in Table 1.2.

	Supply Chain Strategy	
	Efficient	**Responsive**
Primary Purpose	Lowest cost possible	Respond quickly to unpredictable demand
Manufacturing focus	High machine utilization	Excess buffer capacity
Inventory strategy	Minimize inventory	Buffer stocks of parts and finished goods
Lead time focus	Shorten lead time as long it doesn't increase cost	Aggressively reduce lead time
Supplier selection	Cost	Speed and flexibility
Product design strategy	Maximize performance and minimize cost	Postpone product differentiation as long as possible

Source: Fisher, 1997

Table 1.2: Characteristics of efficient and responsive supply chains:

Researchers have tested the Fisher Model explicitly and in the broader sense that a supply chain with an aligned SCS and product type will outperform a supply chain with a misaligned SCS and product type. The research examining the Fisher Model has considered several industries and has employed a variety of methodologies: survey (Ramdas and Spekman, 2000; Selldin and Olhager, 2007; Sun et al., 2009; Lo and Power, 2010; Qi et al., 2011), case studies (Catalan and Kotzab, 2003; Wong et al., 2006; Pero et al., 2010; Khan et al., 2012; Sharifi et al., 2013), statistical analysis (Randall and Ulrich, 2001), and mathematical programming (Wang et al., 2004;Harrison et al., 2010) . All the articles listed above found at least partial support for the Fisher Model, with the exception of Lo and Power (2010). Lo and Power (2010) surveyed Australian manufacturers from a variety of industries and found no statistically significant relationship between the seven demand characteristics Fisher (1997) used to classify product type and the SCS of the firms. The findings from research examining the Fisher Model lead to the first question this dissertation considers:

Q1: Under what circumstances does a supply chain with a misaligned SCS and product type outperform a supply chain with an aligned SCS and product type?

1.2 Supply chain strategy

Researchers have expanded upon the Fisher Model by considering other demand and/or supply characteristics of a product that could impact the selection of the appropriate SCS: product uniqueness (Lamming et al., 2000); supply uncertainty (Lee, 2002); level of modularity and postponement (Ernst and Kamrad, 2000); market growth and technological uncertainty (Randall and Ulrich, 2003); and dominant stage of the PLC (Cigolini et al., 2004, Vonderembse, 2006). Researchers have found that some products exhibited demand characteristics of both functional and innovative products (Lee, 2002; Ernst and Kamrad, 2000; Li and O'Brien, 2001; Christopher and Towill, 2002; Huang et al. 2002; Cigolini et al., 2004; Wong et al., 2006; and Lo and Power, 2010). Products that exhibited characteristics of both functional and innovative products may require a SCS that combines a lean SCS and an agile SCS about a decoupling point, Ernst and Kamrad (2000) referred to this as a postponed SCS. This dissertation classifies a SCS where a lean SCS is used upstream of the decoupling point and an agile SCS is used downstream from the decoupling point as a "leagile SCS". Ernst and Kamrad (2000) and Lee (2002) identified a fourth SCS exhibited with some agricultural products, where supply uncertainty was high and demand uncertainty was low. Both suggested a strategy of utilizing multiple suppliers to minimize the uncertainty in supply; Ernst and Kamrad (2000) referred to this strategy as a modularized SCS and Lee (2002) referred to this as a risk-hedging SCS. This dissertation considers an alternative strategy, where an agile SCS is used upstream of the decoupling point and a lean SCS is used downstream from the decoupling point, denoted as an “agilean SCS”. Therefore, this dissertation considers four supply chain strategies (lean, leagile, agile, and agilean). This leads to the second question this dissertation considers:

Q2: Under what combination of supply chain characteristics will each SCS minimize total supply chain cost?

1.3 Product life cycle and supply chain strategy

A review of the literature reveals two views concerning whether the SCS of a product should change during the life cycle of the product. The first view is that the SCS of a product should change as the product progresses through its life cycle (Lamming et al., 2000; Christopher and Towill, 2000; Childerhouse et al., 2002; Aitken et al., 2003; Holstrom et al., 2006; Jeong, 2011). The second view is the SCS of a product should be determined prior to the product’s introduction to the market and the SCS should be fixed for the entire PLC (Randall and Ulrich, 2001; Cigolini, 2004; Stradtler, 2005; Juttner et al., 2006; Seuring, 2009). Vonderembse et al. (2006) suggested that the SCS should be fixed for the PLC of functional and hybrid products, and for an innovative product the SCS should start with an agile SCS and switch to a leagile SCS or lean SCS for the maturity and decline stages.

The classical PLC model (Figure 1.2) has four stages: introduction, growth, maturity, and decline (Cox, 1967). The introduction and growth stages are characterized by demand instability and higher margin contribution compared to the maturity stage, which is characterized by greater demand stability and lower margin contribution (Rink and Swan, 1979). During the introduction stage of a product, the level of market acceptance, the diffusion rate of the innovation, and the response of competitors are impossible to know with certainty. This market instability results in higher demand uncertainty, similar to an innovative product. During the growth stage, the product experiences an increase in unit sales per time period at a diminishing rate with diminishing margin contribution. The diminished growth rate and margin contribution are the result of increased competition and increased product saturation level in the market place. Once a product reaches the maturity stage, the product exhibits characteristics more typical of a functional product as demand stabilizes and forecast accuracy improves.

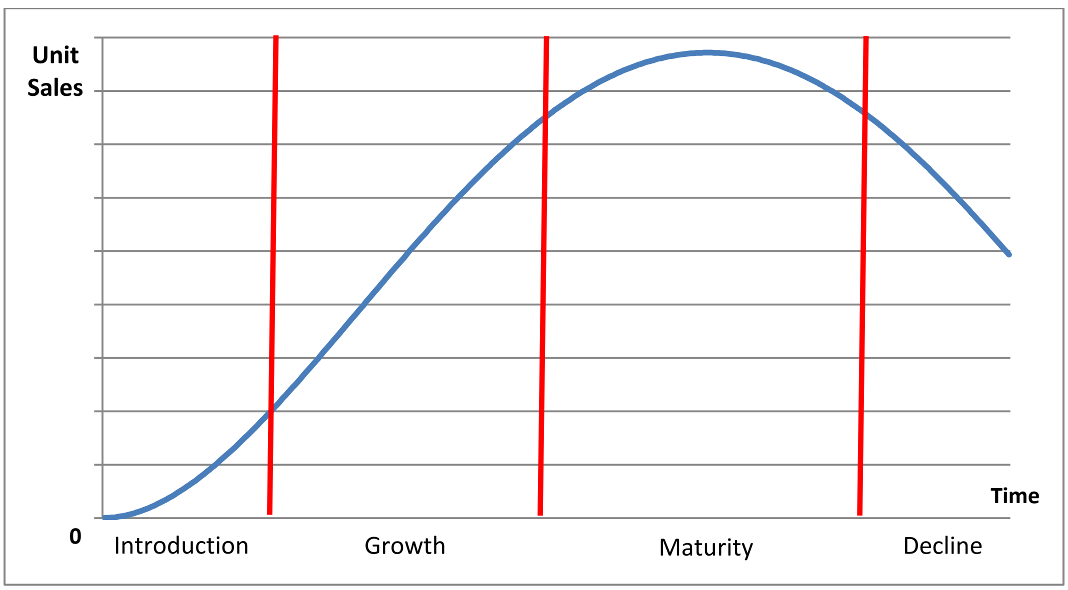


Figure 1.2: Classical product life cycle (Source: Rink and Swan, 1979)

Based on Rink and Swan's (1979) description of the demand characteristics of a product as it progresses through its life cycle and Fisher's (1997) demand characteristics to identify product type, a product's demand characteristics will typically evolve from innovative to functional as it progresses through its life cycle. Accepting the premise that for supply chain management to be successful the product type must be aligned with the SCS (Fisher 1997), then the SCS of a product should evolve as the demand characteristics evolve over the life cycle of the product. One possible evolution of the appropriate SCS for a product is to start with an agile SCS during the introduction stage, then evolve to a compound strategy of either leagile SCS or agilean SCS during the growth stage, and finally evolve to a lean SCS during the maturity stage. Figure 1.3 illustrates a possible alignment of the stages of the PLC, the Fisher Model, and evolving supply chain strategies.

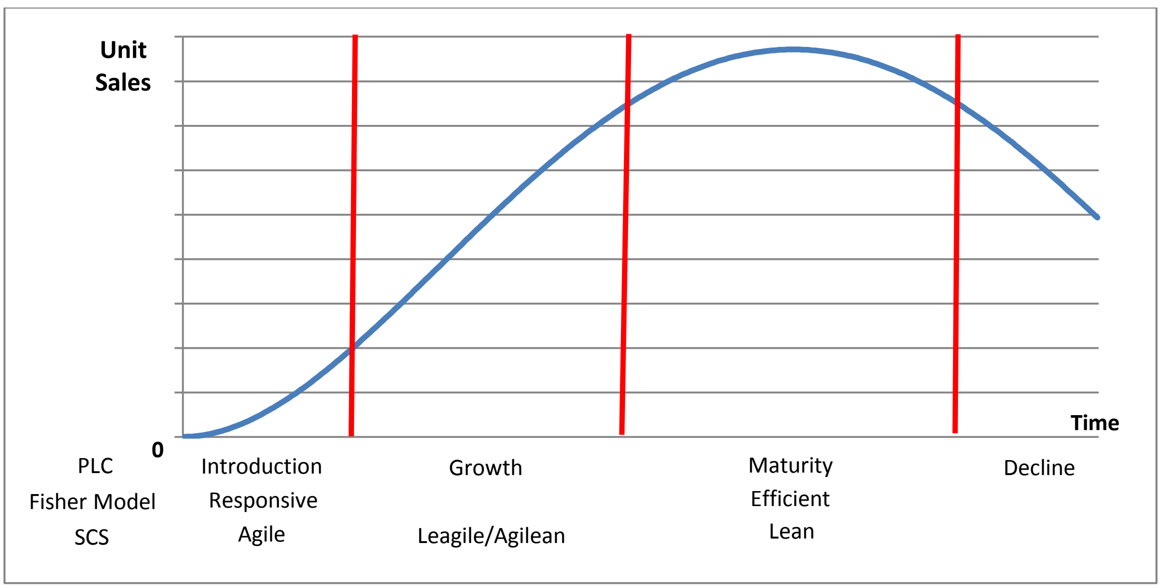


Figure 1.3: Alignment of PLC, Fisher Model, and SCS based on manufacturing paradigms

However, the supply chain might incur costs to change the SCS of a product during its PLC and these costs may exceed the potential benefits to the supply chain from changing the SCS. In practice we can find examples of very successful firms, for example Dell

Inc., which employ a single SCS for the entire life cycle of a product. The leagile SCS employed by Dell Inc. to manufacture, assemble, and direct ship consumer customized personal computers has been well documented in the literature (e.g., Simchi-Levi et al., 2008).

In contrast to the preceding discussion where the SCS may change over the PLC, the literature concluding the SCS of a product should be determined prior to market introduction considered supply chain management in a broader sense, as the planning and management of information and material flows between organizations from raw materials to the end consumer. Upon further examination of the literature that recommended the SCS of a product should change during the PLC, more accurate conclusions from the research concluding the SCS should change over the PLC are (i) the method employed by the firm to convey demand information to the operations department and (ii) the operational strategy of a single echelon should change during the PLC. The articles that concluded the SCS should change over the PLC seem to use an earlier definition for supply chain management as the planning and management of information and material flows between the functional departments within an organization (Lamming et al., 2000).

A portion of the definition of "supply chain management" by Council of Supply Chain Management Professionals is, "… In essence, supply chain management integrates supply and demand management within and across companies" (CSCMP, n.d.). The broader definition of supply chain management incorporates the planning and management of information and material flows both within the organization and between supply chain members. This dissertation expands on the previous research that considered the broader definition of supply chain management. This leads to the third question this dissertation considers.

Q3: Under what combination of supply chain characteristics does each SCS minimize total supply chain cost over the life cycle of a product?

1.4 Methodology

Analytical modeling is a valuable technique that may be employed to examine the overall performance of a system. This modeling method is utilized to provide strategic managerial insights as to how an objective (e.g. minimize total cost) is impacted as parameters and/or the relationship of parameters are varied. This dissertation presents an analytical model for the total supply chain cost when expected demand and demand forecast error are a function of time. The system is modeled as a three echelon supply chain (supplier, manufacturer, and customer) with a decoupling point at the manufacturer and two inventory points, illustrated in Figure 1.4. This formulation allows for four possible supply chain strategies to be considered: (1) agile SCS, where both the supply side and demand side of the supply chain utilize an agile strategy; (2) lean SCS, where both the supply side and demand side of the supply chain utilize a lean strategy; (3) leagile SCS, where the supply side of the supply chain utilizes a lean strategy and the demand side of the supply chain employs an agile strategy; and (4) agilean SCS, where the supply side of the supply chain utilizes an agile strategy and the demand side of the supply chain employs a lean strategy.

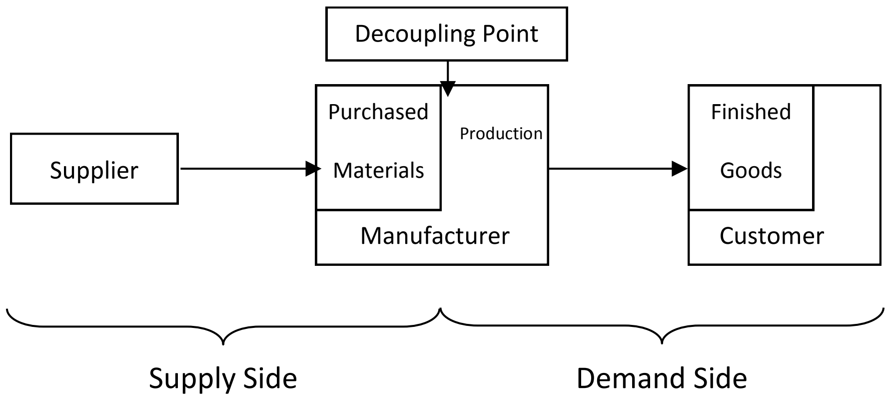


Figure 1.4: Three echelon supply chain with two inventory points

There are a number of criteria that a firm may adopt for evaluating the performance of a SCS, including but not limited to: maximize profit (Guillen et al., 2005), minimize total cost (Kim and Ha, 2003; Ahn and Kaminsky, 2005; Naim, 2006), maximize responsiveness (Agarwal et al., 2006), minimize inventory cost (Gupta and Benjaafar; 2004), and minimize cost deviations (Jeong, 2011). The criteria may also include multiple objectives (Li and O'Brien, 1999; Li and O'Brien, 2001; Herer et al., 2002; Franca et al., 2010). In addition, accounting for the timing of the incurrence of costs or realization of revenues in a supply chain can be a critical determinant of the total net present value (NPV) of the SCS (Kilbi et al., 2010). This dissertation considers the single strategic objective of minimizing the total NPV of supply chain costs (Total Cost), which in the event that revenues are fixed (or independent of the SCS) also maximizes the NPV of profit.

To address the three questions presented earlier, this dissertation considers the impact of four key product related characteristics: ratio of manufacturing cost to purchased material cost (*RMP*), demand forecast error, lean index, and cost of capital (CoC). *RMP* is the ratio of demand side cost per unit to supply side cost per unit, similar to the value-added capacity parameter considered in Li and O'Brien (2001). *RMP* allows examination of how the location of where costs are incurred in the supply chain impacts the selection of the appropriate SCS for a product. Demand forecast error is used as a measure of demand uncertainty, similar to Harrison et al. (2010). Lean index is the ratio of total production cost of an agile SCS to a lean SCS for a product. Cost of capital is used to not only to measure the relative value of money with respect to time, but also as an indication of the risk associated with holding inventory arising from such issues as product obsolescent or spoilage (Naim, 2006). This dissertation considers three levels for each of the four characteristics: high, medium, and low.

1.5 Outline

The remainder of the research is presented in six chapters. Chapter 2 provides a review of the relevant literature and identifies the literature gaps which provide the rationale for this research. Chapter 3 presents the design and methodological underpinnings of the analytical model. Chapter 4 addresses Q1: Under what circumstances does a supply chain with a misaligned SCS and product type outperform a supply chain with an aligned SCS and product type? This is modeled with expected demand and demand forecast error held constant for a forecast period. Chapter 5 addresses question Q2: Under what scenarios does each SCS minimize total supply chain cost? This is modeled with expected demand increasing or decreasing and demand forecast error constant for a forecast period. Chapter 6 addresses question Q3: Under what scenarios does each SCS minimize total supply chain cost over the life cycle of a product? This is modeled with expected demand mimicking the classical PLC and demand forecast error improving with time. Chapter 7 summarizes the findings of the research, provides managerial insights, discusses the limitations of the research, and identifies areas of possible future research.

2. Literature review

The following literature review is not intended to be a review of the 2800+ citations Fisher (1997) has received since publication, but instead a review of the literature examining supply chain strategy selection. This chapter is subdivided into seven sections: (1) Supply chain strategy selection frameworks, (2) Research testing the hypothesis that the alignment of product and market characteristics with supply chain strategy improved supply chain performance, (3) Lean/leagile/agile supply chain strategies, (4) Supply chain strategy over the life cycle of a product, (5) Mathematical programming and simulation models for supply chain strategy selection, (6) Analytical models of supply chain strategy, and (7) Supply chain management models considering net present value.

2.1 Supply chain strategy selection framework

Supply chain management is an umbrella-like managerial concept encompassing many functional areas both within and between firms, with logistics being a key functional area of supply chain management. Fuller et al. (1993) described how one single logistical strategy may not be appropriate for all customers. Similarly, Fisher (1997) discussed the realization that one SCS did not fit all products. The Fisher Model provided a framework to assist companies with identifying the appropriate SCS for a product based on the demand characteristics of the product. The model classified products as either functional or innovative, where the supply chain of a functional product should be an efficient SCS and the supply chain of an innovative product should be a responsive SCS. Several publications have expanded upon the Fisher Model by considering additional demand and supply characteristics of the product that could influence the SCS decision (Pagh and Cooper, 1998; Lamming et al., 2000; Ernst and Kamrad, 2000; Randall and Ulrich, 2001; Christopher and Towill, 2002; Huang et al., 2002; Lee, 2002; Cigolini et al., 2004; Wong et al., 2006; Vonderembse et al., 2006). The purpose of these frameworks was to assist practitioners with identifying the correct SCS for their products. The authors used a variety of names for essentially the same supply chain strategies. In this chapter, the SCS classification used in this dissertation (lean, agile, leagile, or agilean) that is most similar to the article's SCS name is provided immediately following in parenthesis.

Pagh and Cooper (1998) presented a SCS framework based on the level of postponement in logistics and manufacturing. Each determinate of the framework was evaluated at two levels, speculation or postponement. With the logistics determinant, logistics speculation employed a decentralized inventory system, while logistics postponement utilized a centralized inventory system with a direct distribution strategy. The manufacturing speculation level was a make-to-stock inventory strategy, while the manufacturing postponement level was a make-to-order strategy. The framework of logistics and manufacturing postponement resulted in four possible supply chain strategies. The first strategy was full speculation (lean SCS) which employed a make-to-stock manufacturing strategy and a decentralized inventory system with a primary focus on cost minimization. The second strategy was logistics postponement, where the manufacturing strategy was make-to-stock and the distribution strategy was direct ship to the customer. The third strategy was manufacturing postponement (leagile SCS), which combined a make-to-order manufacturing strategy and a decentralized inventory system, with some manufacturing completed at the warehouse close to the customer. The fourth strategy was full postponement (agile SCS), with a make-to-order manufacturing strategy and a centralized inventory system.

Ernst and Kamrad (2000) presented a conceptual framework that identified four possible supply chain structures dependent upon the degree of outbound postponement and inbound modularization: rigid (lean SCS), postponed (leagile SCS), modularized, and flexible. The modularized SCS was a strategy that utilized multiple suppliers to mitigate the risk from supply uncertainty, and the flexible SCS was a combination of the postponed and modularized SCS. The framework was evaluated using an analytical model with an objective of total cost minimization. The paper presented a scenario analysis of a supply chain serving two markets with separate service levels and demand uncertainty levels. The total cost function was the summation of fixed, variable, inventory holding, and backorder costs as a function of demand and was independent of time. The authors concluded that a rigid supply chain structure (lean SCS) minimized total cost when the service level and demand variability of the two markets were similar and a flexible supply chain structure (agile SCS) minimized total cost when the difference between the service level and demand uncertainty of the two markets was high.

Lamming et al. (2000) extended Fisher (1997) by considering the uniqueness of the product. The authors argued that the correct SCS was not only dependent upon whether the product was classified as innovative or functional, as Fisher (1997) described, but also the uniqueness of the product. A product was defined as unique if it has a characteristic which differentiated it from its competitors and the unique characteristic provided a competitive advantage. The authors suggested that the category names “innovative-unique” and “functional” more accurately described the categories of product types which determine SCS. To examine this premise the authors conducted semi-structured interviews of senior personnel at 16 firms. The firms interviewed were from 5 industry groups; automotive, fast moving consumer goods, electronics, pharmaceuticals and service. From the qualitative analysis of the semi-structured interviews, the authors found that the uniqueness of the product impacted the SCS a firm employed, and that firms employed a responsive SCS (agile SCS) for unique products. In addition, the analysis found support for Fisher’s contention that the appropriate SCS for a product was dependent upon the demand characteristics of that product.

Randall and Ulrich (2001) provided an analysis of the U.S. mountain bicycle industry in research that examined the impact the alignment of product type (production or market) and SCS (local vs. distant) had on the firm’s performance. The article identified product type as either production driven or market driven. The two supply chain strategies considered were local or distant; a local SCS (agile SCS) had production operations near the end consumer (in the U.S.) and a distant SCS (lean SCS) had production operations located off-shore. The paper found that firms with production driven products and a distant SCS (lean SCS), and firms with market driven products and a local SCS (agile SCS), outperformed those firms with production driven products and a local SCS (agile SCS), and with market driven products and a distant SCS (lean SCS). The analysis supported Fisher’s (1997) contention that firms with an aligned SCS and product type outperformed those firms with a misaligned SCS and product type.

Christopher and Towill (2002) presented a case study of a United Kingdom garment company to illustrate a SCS framework for selecting the correct SCS based on the product characteristics, demand characteristics, and replenishment lead-time of the pipeline. The framework classified products as either standard or special; these terms were analogous to Fisher's (1997) product types of functional or innovative, respectively. According to this framework, an innovative agile SCS (agile SCS) was proper when the product type was special, demand was volatile, and lead-time was short. A top-up agile SCS, a type of leagile SCS which employed a "base and surge" strategy discussed later in the literature review, was appropriate when the product type was standard, demand was volatile, and lead-time was short. A high volume lean SCS (lean SCS) was correct when the product type was standard, demand was stable, and lead-time was long. The framework was later evaluated in a case study of a United Kingdom apparel organization with a global supply chain and a single SCS for all products (Christopher et al. 2006). The research found that by adopting a "base and surge" leagile strategy, the organization was able to improve profitability and service levels.

A conceptual framework that married the manufacturing paradigms of lean, agile, and leagile with the supply chain strategies of efficient and responsive from Fisher (1997) was developed by Huang et al. (2002). The framework was a 3x3 matrix with SCS on one axis and product type on the other. From the model, an agile SCS (agile SCS) was the correct strategy for an innovative product; the hybrid SCS, where a lean and agile supply chain were employed in parallel, similar to the leagile Pareto strategy discussed later in section 2.3, was the appropriate strategy for a hybrid product; and a lean SCS (lean SCS) was the correct strategy for a standard product.

Where Fisher (1997) focused on demand uncertainty as the key for matching the correct SCS to product type, Lee (2002) extended the focus on uncertainty by including supply uncertainty. To illustrate the significance of supply uncertainty, Lee (2002) used examples from the food and fashion industries. An agriculture product was often considered a functional product with low demand uncertainty, but due to the uncertainty of weather the supply uncertainty was high. A fashion product was considered an innovative product with high demand uncertainty, but the supply base was stable and therefore had low uncertainty using proven manufacturing techniques. Four supply chain strategies were presented depending on the stability of supply and demand uncertainty: an efficient SCS (lean SCS) when supply and demand uncertainty were both low; an agile SCS (agile SCS) when supply and demand uncertainty were both high; a responsive SCS (leagile SCS) when supply uncertainty was low and demand uncertainty was high, and a risk-hedging SCS when supply uncertainty was high and demand uncertainty was low.

Olhager (2003) discussed the order penetration point (OPP) of a supply chain in the terms of operational strategies: make-to-stock (MTS) (lean SCS), make-to-order (MTO) (agile SCS) and assemble-to-order (ATO) (leagile SCS). A 2x2 framework for operational strategy was presented based on the ratio of production lead time (P) to delivery lead time (D) and the relative demand volatility (RDV). The RDV of a product's demand was its coefficient of variation. The model identified the appropriate SCS for the following combinations of P/D and RDV. When P/D<1 and RDV was high, a MTO (agile SCS) was appropriate; when P/D>1 and RDV was low, a MTS (lean SCS) was appropriate; when P/D<1 and RDV was low, then a combination of MTO and MTS (leagile SCS) was appropriate; and when P/D>1 and RDV was high, then an ATO (leagile SCS) was appropriate. The difference between the make-to-stock and the assemble-to-stock strategies were the locations of the decoupling point in the supply chains. According to the author, the ATO SCS was the least desirable and a firm should take action to either reduce the P/D ratio to less than one or reduce the RDV of the product. The article provided a discussion concerning the reasons for shifting the OPP forward or backwards in the supply chain, as well as the competitive advantages and negative effects resulting from an OPP shift.

Cigolini et al. (2004) presented a framework for identifying the appropriate SCS based on the product type and the dominant stage of the PLC. The framework considered three supply chain strategies: efficient (lean SCS), lean (leagile SCS), and quick (agile SCS). The descriptions used by the authors to describe the primary focus of each SCS type were as follows: an efficient strategy focused on price, a lean strategy focused on price and time, and a quick strategy focused on time. The framework illustrated that a product with a dominant introduction and decline stage of the PLC required a quick SCS (agile SCS). For products where the growth stage of the PLC was dominant, a lean SCS (leagile SCS) was appropriate. Products with a dominant maturity stage were subdivided into two categories, complex and simple. Complex products with a dominant maturity stage of the PLC should employ a lean SCS (leagile SCS) and simple products with a dominant maturity state of the PLC should utilize an efficient SCS (lean SCS). Data used to test this framework was borrowed from previously published works. The authors' analysis found support for the framework.

Vonderembse et al., (2006) presented a framework that the decision to change SCS during the PLC was dependent upon the product type. The paper considers three product types: standard, innovative, and hybrid. A standard product should employ a lean SCS (lean SCS) for the life cycle of the product. A hybrid product should adopt a hybrid

SCS (leagile SCS) for the life cycle of the product. However, an innovative product should utilize an agile SCS (agile SCS) during the introduction and growth stages of the PLC and then change to either a leagile SCS or lean SCS for the maturity and decline stages of the PLC. Three case studies were presented to support the SCS/PLC framework.

A case study utilizing the Fisher Model to assist in the selection of the appropriate SCS for 667 toy products from a single manufacturer was presented by Wong et al. (2006). The article considered four supply chain strategies: made-to-order, physically efficient (lean SCS), physically responsive (lean SCS), and market responsive. The authors indicated a made-to-order SCS should be employed for products that were termed as “suicide” products, products with high forecast uncertainty and low contribution margin. Due to the long production lead-time, the physically efficient and physically responsive strategies both utilized a make-to-stock (MTS) strategy, but with slightly different inventory policies. The market responsive SCS was a “base and surge” leagile SCS, where initial orders were supplied by a MTS strategy and subsequent orders were filled using an assemble-to-order (ATO) strategy. Using forecast uncertainty, contribution margin, and demand variability, the products were grouped into three clusters. The paper presented a framework model, which was an extension of the Fisher Model with two determinants. Both of the determinants, contribution margin and forecast uncertainty, were measured on a scale from low to high. The framework presented suggests that a physically efficient SCS (lean SCS) was appropriate when both forecast uncertainty and contribution margin were low, a market responsive SCS was appropriate when both forecast uncertainty and contribution margin were high, and a physically

	Supply Chain Strategy – Objective or Construction								
			Leagile						
Supply Chain Strategy Framework	**Cost Minimization**	**Responsive**	**Decoupling Point**	**Base and Surge**	**Parallel (Pareto)**	**Direct Ship**	**Multiple Suppliers**	**Build-to-order**	**Agilean**
Fisher (1997)	Efficient	Responsive							
Pagh & Cooper (1998)	Full Speculation	Full Postponement	Manufacturing Postponement			Logistics Postponement			
Lamming et al. (2000)	Efficient	Responsive							
Ernst & Kamrad (2000)	Rigid	Flexible	Postponed				Modularized		
Randall & Ulrich (2001)	Distant	Local							
Christopher & Towill (2002)	High Volume Lean	Innovative Agile		Top-up Agile					
Huang et al. (2002)	Lean	Agile			Hybrid				
Lee (2002)	Efficient	Agile	Responsive				Risk-Hedging		
Olhager (2003)	Make-to-stock	Make-to-order	Assemble-to-order and MTS/MTO prior to assembly						
Cigolini et al. (2004)	Efficient	Quick	Lean						
Wong et al. (2006)	Physically Efficient and Physically Responsive (MTS)			Market Responsive (MTS and ATO)				Made-to-order	
Vonderembse (2006)	Lean	Agile	Hybrid						
Ellegood (2014)	Lean	Agile	Leagile						Agilean

Table 2.1: Supply chain strategy classifications from the literature.

responsive SCS (lean SCS) was appropriate when both forecast uncertainty and contribution margin were neither low nor high.

The relationship of the SCS classifications considered by the papers reviewed in this section and the SCS classification system presented in this dissertation are shown in Table 2.1. Although the nomenclature used to classify supply chain strategies and the characteristics used to determine the appropriate SCS differ slightly, two key characteristics, demand uncertainty and response time, appear in almost all the frameworks either as a primary characteristic or as a characteristic that impacts SCS selection. When demand uncertainty is low, the SCS should focus on cost minimization first and response time reduction second. When demand uncertainty is high the SCS focus should be on response time reduction first and cost minimization second.

2.2 Examining the Fisher Model and supply chain strategy alignment

This section summarizes those articles that explicitly evaluated the Fisher Model (Catalan and Kotzab, 2003; Wong et al., 2006; Selldin and Olhager, 2007; Lo and Power, 2010, Harrison et al, 2010) and those articles that evaluated the larger concept of SCS alignment (Ramdas and Spekman, 2000; Sun et al., 2009; Pero et al., 2010; Qi et al., 2011; Khan et al., 2012; Sharifi et al., 2013). The purpose for examining the literature in this section is to verify the validity of the Fisher Model and the assertion that supply chain performance is impacted by the alignment of SCS and demand characteristics.

Ramdas and Spekman (2000) examined three questions concerning the Fisher Model: (i) did the SCS of supply chains differ between product types?; (ii) did the top supply chain performers of innovative products focus on revenue enhancement more than the top supply chain performers of functional products?; and (iii) did the reasons a firm engages in supply chain management and the practices employed differ between top and bottom performers for both product types and between the supply chain strategies? The authors surveyed 160 firms from six industry groups. The questions used to classify the products as either innovative or functional were based on Porter (1985) and included: limited availability of substitutes, rapid changes in market conditions, rapid changes in technology, low market maturity, and short PLC. Respondents were asked to score their product based on a 1-7 Likert scale, with their responses summed to create a market-stability index. Those responses in the top third of the market-stability index were classified as innovative and those in the bottom third were identified as functional. Respondents also indicated the product's supply chain performance based on a 1-7 Likert scale in six areas: inventory, time, order, fulfillment, quality, and customers. In addition, the survey included 20 to 30 questions for each of the following areas: information practices, partner selection, and reasons for engaging in supply chain management. The author's concluded: (i) the supply chain practices and reason for engaging in supply chain management differed between the supply chains of innovative and functional products; (ii) the top performers who produced innovative products did utilize supply chain practices that enhanced revenues more than the top performers who produced functional products; and (iii) those practices that separated top performers from lower performers did differ between the supply chains of innovative and functional products.

To explore whether an industry employed a responsive SCS for innovative products, Catalan and Kotzab (2003) examined the supply chains of Danish mobile phone producers. The research data was collected from unstructured interviews and surveys of ten industry experts concerning four aspects of responsiveness: lead-time, postponement strategies, bullwhip effect, and information exchange. The authors found that although mobile phones would be categorized as an innovative product, the supply chains examined severely lacked responsiveness. The Danish mobile phone producers had excessive inventories of the wrong products, long lead-times, and a lack of collaboration and information exchange between supply chain members. The authors concluded that the poor performance of the Danish mobile phone supply chains was the result of a mismatch between SCS and the product type.

To examine the question of whether the SCS of a product should be set at the time of initial market entry, Randall et al. (2003) conducted a statistical analysis of the North America mountain bike industry. According to the authors, a common product life-cycle for a bicycle was five years, while the expected life of a bicycle production facility was twenty-five years. The data for the analysis came from industry publications between the years 1985 to 1999. From the data, the rate of market growth, relative product contribution margins, amount of product variety, and level of uncertainty (demand and technological) were used to characterize product demand conditions. Those firms with both painting and assembly operations located in North America were characterized as having a responsive SCS (agile SCS); all others were characterized as having an efficient SCS (lean SCS). The data supported the hypothesis that lower market growth rates would be associated with an increase in the number firms that employed a responsive SCS entering the market. Low market growth rates were associated with a mature market; therefore, those firms entering the market would be targeting niche markets and thus should utilize a responsive SCS (agile SCS). The hypothesis that periods of higher contribution margins for responsive supply chains would be associated positively with new firms employing a responsive SCS (agile SCS) entering the marketing was also supported. In addition, the research found that as the product variety in the industry increased, there was an increase in the number of firms entering the market with a responsive SCS (agile SCS). An increase in technological uncertainty was found to be positively associated with an increase in responsive SCS (agile SCS) entries; however the association with demand uncertainty was not statistically significant. This could be because the demand uncertainty levels of the products were relatively low and at a level that would classify the products as functional products using Fisher (1997).

Selldin and Olhager (2007) surveyed 128 Swedish manufacturers to answer two questions concerning Fisher (1997): "Do companies follow the prescribed fit between products and supply chain?" and "Are companies with a good fit between products and supply chains better performers than companies with a poor fit?" The survey instrument considered all seven of the product characteristics presented in Fisher (1997); however the product characteristic of "average forced end-of-season markdown" was dropped from the analysis due to a low response rate. The survey instrument considered five of the six supply characteristics as described by Fisher (1997), excluding "product design strategy." The analysis of the survey found products located in all four quadrants of the Fisher Model. When evaluating the hypotheses, the authors excluded those survey responses where the product type or SCS could not clearly be identified, leaving 68 responses. The statistical analysis found support that companies with functional products chose an efficient SCS (lean SCS) rather than a responsive SCS (agile SCS) and those companies that employed an efficient SCS (lean SCS) produced functional products more than innovative products. However, the statistical analysis did not support that companies with innovative products utilized a responsive SCS (agile SCS) rather than an efficient SCS (lean SCS), nor that companies that employed a responsive SCS (agile SCS) produced innovative products rather than functional products. Respondents scored their own performance relative to their competitors' performance, and results were compared for firms with a "Match" vs. firms with a "Mismatch" of product type and SCS, according to Fisher (1997), and the respondents in the "Match" category outperformed those in the "Mismatch" category in the areas of cost, delivery speed and delivery dependability. However, for the areas of product quality, volume flexibility, product mix flexibility and profitability there was not a statistically significant difference between the firms in the "Match" and "Mismatch" categories. The study found support for the Fisher Model, in that firms who had an aligned SCS and product type outperformed their competitors in some performance measures. The survey also found that products were not always easily classified as either functional or innovative and that supply chain strategies were not always easily classified as either efficient or responsive.

Sun et al. (2009) examined whether the performance of a firm with an aligned SCS and environmental uncertainty (demand and supply uncertainty) was better than those firms with a misaligned SCS and environmental uncertainty. The paper considered four supply chain strategies, taken from Lee (2002): efficient (lean SCS), responsive (leagile SCS), risk-hedging, and agile (agile SCS). A total of 243 Taiwan manufacturing companies participated in the survey, which considered nine attributes. Five of the attributes examined were manufacturing related: price, flexibility, quality, delivery, and service. The remaining four attributes examined information systems capabilities:

operational support systems, market information systems, inter-organizational systems, and strategic decision support systems. The authors concluded that there was a statistically significant positive relationship between the performance of firms and the degree of alignment of SCS and demand and supply uncertainty.

Pero et al. (2010) provided insight into the effect that aligning new product development and supply chain management had on the performance of the supply chain. To research this issue, they conducted five case studies covering four industries. The variables related to new product development included modularity, product variety, and innovativeness. The supply chain management variables included the supply chain configuration, level of collaboration, and coordination complexity. The level of performance of the supply chain was measured based on the supply chain's ability to satisfy customer orders during product launch. The authors concluded that the performance of the supply chain was dependent upon aligning new product development and supply chain strategy.

To study the question, "does Fisher's (1997) model represent the association between product nature and supply chain strategy appropriately?", Lo and Power (2010) surveyed 107 managers from a wide variety of manufacturing industries in Australia. When using the seven product characteristics described in Fisher (1997) to classify product type, 23 products were classified as functional and zero were classified as innovative. The researchers did not test the validity of the Fisher Model using this classification; instead, the products were reclassified as functional or innovative based on the mean value of the survey responses by the managers to the seven product characteristics. Those products where all seven responses were less than the mean value were reclassified as functional (70) and the remaining products were reclassified as innovative (37). The details of the new scale were not provided. With the new classification scheme the authors found no statistical support that firms with a functional product emphasized an efficient SCS (lean SCS), nor that firms with an innovative product emphasized a responsive SCS (agile SCS).

Harrison et al. (2010) utilized commercially available supply chain optimization software, Logic Tools, Inc., to investigate the validity of Fisher's model. The model was populated using data from the *Bicycle Retailer & Industry News* (Carpiet, 2006). Two four-echelon supply chains were modeled, one identified as "physically efficient" (lean SCS) with materials sourced and production in the Far East and the second, "market responsive" (agile SCS) with materials sourced and production located domestically. The paper did not include information concerning the material and production costs or the lead times used to model each SCS. Each SCS was considered for 10 products, with 5 functional and 5 innovative. The demand forecast error of the functional products was set at 10%, the contribution margin ranged from 5% to 20% and the stock-out rate ranged from 1% to 2%. The demand forecast error of the innovative products ranged from 40% to 100%, the contribution margin ranged from 20% to 60% and the stock-out rate ranged from 10% to 40%. The SCS which resulted in the greatest gross profit was selected as the preferred SCS. The study supported the Fisher Model for those products where the demand characteristics were at the lower end of the Fisher (1997) scale for a functional product (e.g. forecast error of 10%, contribution margin of 5% and stock-out rate of 1%) and for those products where the demand characteristics were at the higher end of the Fisher (1997) scale for an innovative product (e.g. forecast error of 100%, contribution margin of 60% and stock-out rate of 40%). However, an agile SCS resulted in higher gross profit for the functional product with demand characteristics at the upper end of the Fisher (1997) scale for a functional product (e.g. forecast error of 10%, contribution margin of 20% and stock-out rate of 2%), and a lean SCS resulted in higher gross profit for the two innovative products with demand characteristics at the lower end of the Fisher (1997) scale for an innovative product (e.g. forecast error of 40%, contribution margin of 20% and stock-out rate of 10%).

To examine whether the alignment of a firm's competitive strategy (cost leader or differentiation) and SCS (lean or agile) led to better performance, Qi et al. (2011) surveyed 604 China manufacturing firms. In addition, they evaluated the moderating effect uncertainty (demand, supply, and technology) had on a firm's SCS. Variables used to measure a firm's business performance were return on investment (ROI), return on assets (ROA), market share, growth in ROI, growth in ROA, and growth in market share. The research found that business performance of a firm in an environment of low uncertainty was more effectively improved by a lean SCS and for firms in an environment of high uncertainty an agile SCS was more effective at improving business performance. In addition, the research showed that firms with a cost leader strategy in an environment of high uncertainty emphasized improving both lean and agile aspects of the supply chain, noting that in future research the leagile SCS should be included in the study.

Qi et al. (2009) conducted a cluster analysis of the data set utilized in Qi et al. (2011) to identify the supply chain strategy types employed by the 604 China manufacturing firms. The analysis found that the firms were fairly evenly distributed among four supply chain strategy types: agile, lean/agile, traditional, and lean. A firm that employed a lean/agile SCS emphasized both lean and agile strategies and a firm with a traditional strategy emphasized neither lean nor agile strategies.

To investigate the impact of aligning product design and SCS on the resilience and responsiveness of a supply chain, Khan et al. (2012) studied a UK apparel company. The objective of the apparel company was to transform the latest fashion design to products on store shelves in 8-12 weeks with an expected product life for the design of 12 weeks. To achieve this objective the supply chain required changes to the distribution strategy, design strategy, information systems, and sourcing strategies. The distribution strategy reorganized from a decentralized to a centralized strategy with only two distribution centers. The implementation of a centralized distribution system reduced the number of purchase orders, reduced transportation cost through economies of scale, and delayed the point of differentiation, with the distribution center completing final labeling and packaging. The article demonstrated how aligning product design and SCS can greatly reduce the time to market, achieve a responsive distribution strategy, and result in a resilient supply chain through modularity and standardization.

Sharifi et al. (2013) examined the impact of alignment of supplier selection and SCS on new product launches. The researchers considered four case studies from four industries to evaluate the level at which small and medium enterprises (SME) engaged suppliers when developing their market and product growth strategies. The authors concluded that the SMEs did not involve suppliers in the development of the firm's market and product growth strategies, which resulted in disruptions during product launch and limited the growth potential of the firm.

All the literature reviewed, except for Lo and Power (2010), found support for the Fisher Model and that alignment between SCS and demand characteristics resulted in better supply chain performance. However, the literature also found that not all products were easily classified as functional or innovative and that some products exhibit demand characteristics of both. In addition, the literature pointed to a third SCS commonly employed by practitioners. This third SCS was generally described as a SCS that combines a lean SCS and an agile SCS about a decoupling point. Fourth, almost all the literature reviewed in this section employed either survey or case study methodology to examine the Fisher Model. Lastly, there was some evidence that at times a misalignment of demand characteristics and SCS could result in better supply chain performance; however, there was no detailed examination of the combination of supply chain characteristics where this resulted.

2.3 Lean/leagile/agile

The focus of "lean manufacturing" (Womack et al., 1990) and "lean enterprise" (Womack and Jones, 1996) was the elimination of waste or *muda*, where waste was anything (e.g. operation, step, process, inventory, etc.) that did not add value. Lean manufacturing as a manufacturing strategy had its foundation in the Toyota Production System (Ohno, 1998) and its focus on the elimination of waste. The concept of an agile SCS had evolved from the manufacturing strategy of "flexible manufacturing systems", where flexibility was a critical aspect of an agile strategy (Christopher and Towill, 2002). Several articles have related Fisher's (1997) efficient and responsive supply chain strategies to the manufacturing paradigms of lean and agile respectively (Mason-Jones et al., 2000; Childerhouse and Towill, 2000; Stratton and Warburton, 2003; Christopher and

Towill, 2001). When considering SCS as a continuum from agile to lean, with a purely agile SCS and purely lean SCS as opposite endpoints of the continuum, intermediate points would exhibit attributes of both an agile SCS and a lean SCS. A third manufacturing paradigm that combined a lean and agile supply chain strategies about a decoupling point was defined as a leagile SCS by Naylor (1999). The leagile strategy of employing different supply chain strategies about a decoupling point was just one of the leagile strategies that had been discussed in the literature. Three types of leagile strategies from the literature are discussed in this section: decoupling point, base and surge, and Pareto. Leagile (decoupling point) is similar to the SCS of postponement, where an efficient SCS is used up to the point of product differentiation and a responsive SCS is used following this point. The distinguishing attributes of a lean SCS, an agile SCS, and a leagile SCS (decoupling point), as described by Agarwal et al. (2006), are presented in Table 2.2.

Distinguishing Attributes	Lean SCS	Agile SCS	Leagile SCS (Decoupling Point)
Market demand	Predictable	Volatile	Volatile and unpredictable
Product variety	Low	High	Medium
Product life cycle	Long	Short	Short
Customer drivers	Cost	Lead-time and availability	Service level
Profit margin	Low	High	Moderate
Dominant costs	Physical costs	Marketability costs	Both
Stock out penalties	Long term contractual	Immediate and volatile	No place for stock out
Purchasing policy	Buy goods	Assign capacity	Vendor managed inventory
Information enrichment	Highly desirable	Obligatory	Essential
Forecast mechanism	Algorithmic	Consultative	Both/either
Typical products	Commodities	Fashion goods	Product as per customer demand
Lead time compression	Essential	Essential	Desirable
Eliminate muda	Essential	Desirable	Arbitrary
Rapid reconfiguration	Desirable	Essential	Essential
Robustness	Desirable	Essential	Essential
Quality	Market qualifier	Market qualifier	Market qualifier
Cost	Market winner	Market qualifier	Market winner
Lead-time	Market qualifier	Market qualifier	Market qualifier
Service level	Market qualifier	Market winner	Market winner

Source: Agarwal et al. (2006)

Table 2.2: Comparison of lean, agile, and leagile supply chain attributes

Naylor et al. (1999) pointed out that the lean and agile manufacturing paradigms were not separate and isolated strategies to be employed in supply chain management, but could be used in combination, with the strategies separated by a decoupling point. The decoupling point separated the part of the supply chain oriented towards planning (lean) from the portion of the supply chain oriented towards customer orders (agile) (Argelo et al. 1992). Depending on the location of the decoupling point, a supply chain could be classified from buy-to-order to ship-to-stock, as the decoupling point moves from the raw material supplier to the retailer. Naylor et al. (1999) provided a discussion of the similarities and difference of lean and agile manufacturing paradigms, acknowledging that with both a lean SCS and an agile SCS there was a necessity to compress lead times. However, with a lean SCS the objective was cost minimization compared to an agile SCS, where response time reduction was the primary objective. A supply chain with an agile SCS focused on lead time compression in both information and material exchanges. The paper demonstrated that a lean SCS and an agile SCS were not strategies that should be viewed as only either/or, but together as a leagile SCS that could both reduce the total supply chain cost relative to an agile SCS and increase responsiveness of the supply chain to changes in demand relative to a lean SCS.

Mason-Jones et al. (2000a) presented three case studies to illustrate the circumstances under which a lean SCS, an agile SCS, and a leagile SCS should be implemented. The first case was of a United Kingdom manufacturer that employed a lean global supply chain to export its products to the USA, Japan, Korea and Europe. With the implementation of a distribution requirement planning system linked to the customers, the firm was able to greatly improve their forecast accuracy. In addition, the company implemented a kanban system for the production floor. The second case examined a carpet manufacturer where the firm implemented parallel lean and agile supply chains, where the lead time of the lean SCS was four weeks and the lead time of the agile SCS was one week. The products assigned to the lean SCS included 90% of their product offerings and accounted for 48% of total sales. The top 10% of their product offerings accounted for 52% of total sales and were produced under an agile SCS. The third case study was of a leagile SCS at an electronic product manufacturer where components were produced and purchased based on forecasted demand (lean SCS) and the final assembly was scheduled based on actual orders (agile SCS). The case studies were used to demonstrate that a one size fits all approach to SCS was incorrect and that the appropriate SCS depended on the demand characteristics of the market.

Christopher and Towill (2001) discussed various approaches that a supply chain could employ using both a lean and an agile SCS to satisfy customer demand. The article described three approaches: Pareto, “base and surge”, and a de-coupling point. With the Pareto approach the supply chain would utilize a lean SCS for the top 20% of products that satisfy 80% of the demand and an agile SCS for the other 80% of products that satisfy 20% of the demand. The “base and surge” approach was frequently utilized in the fashion industry where a lean SCS was used to satisfy the portion of expected demand that can be forecasted with a high level of confidence, the “base”, and an agile SCS was used to satisfy the portion of demand that was difficult to forecast, the “surge”. The de-coupling point approach was a supply chain where a lean SCS was used up to the de-coupling point, and downstream of the de-coupling point an agile SCS was employed. Towill and Christopher (2002) proposed a framework for firms to adopt both a lean SCS and an agile SCS dependent upon time and space. The article presented three cases, with each case demonstrating one of the strategies presented in Christopher and Towill (2001): base and surge, Pareto, and decoupling.

Aitken et al. (2002) presented a case study of a United Kingdom lighting company where several of their product families had become commodity products with offshore competitors competing on price. The United Kingdom firm was unable to reduce costs to a point that would allow them to compete on price, so they adopted an agile SCS to improve customer service. To achieve the new agile SCS, the United Kingdom lighting company had to significantly reduce lead times. The firm's products were segmented based on a framework where the appropriate SCS was dependent upon the level of product variety and demand predictability.

Stratton and Warburton (2003) examined how the supply chain strategies of lean and agile could be integrated. The authors pointed out that many firms produced a variety of products with different levels of demand uncertainty and that a one size fit all SCS was not appropriate to satisfy customer expectations. Products could be separated into groups based on space, "whole and its parts", time, or condition to determine the appropriate SCS for a product or a group of products. Separation in space was separating based on different business environments, such as stable versus unstable demand. Separation of a "whole and its parts" was separating the SCS about a decoupling point as in a leagile SCS. Separation in time was adopting a "base and surge" strategy, where the stable portion of demand was supplied by the lengthier lean SCS and the unstable portion was supplied by the shorter agile SCS. Separation upon condition was separating on order winning criteria, such as price (lean SCS) and delivery speed (agile SCS). A framework for identifying the appropriate SCS based on product type (special or standard) and demand uncertainty (volatile or stable) was presented where an agile SCS was indicated when demand uncertainty was volatile and independent of the product type, and a lean SCS was suggested for standard product type with low demand uncertainty (stable).

Naim and Gosling (2011) provided an examination and classification of the citations of Naylor et al. (1999). Only one article reviewed explored the relationship between SCS and PLC (Vonderembse et al. 2006). Overall the articles reviewed show strong support for a third SCS, leagile, which combined lean and agile strategies about a decoupling point. Most articles also noted that a leagile SCS, like a lean SCS and an agile SCS, was neither better nor worse than the other supply chain strategies and that the appropriate SCS for a product was dependent on a combination of factors.

2.4 Product life cycle and supply chain strategy

The literature examining SCS over the PLC can be grouped into two categories: (1) the SCS should change over the PLC as the demand characteristics of the product change (Christopher and Towill, 2000; Childerhouse et al., 2002; Aitken et al., 2003; Holstrom et al., 2006; Jeong, 2011); and (2) the SCS for a product should be determined prior to market introduction and should not change over the PLC (Randall and Ulrich, 2001; Cigolini, 2004; Stradtler, 2005; Juttner et al., 2006; Vonderembse et al., 2006; Seuring, 2009). As a product progresses through its PLC, the classification of the product as innovative or functional may change. The classical PLC model has four stages: introduction, growth, maturity, and decline (Cox, 1967). The introduction and growth stages are characterized by demand instability and higher margin contribution compared to the maturity stage, which is characterized by greater demand stability and lower margin contribution (Rink and Swan, 1979).

A case study of a United Kingdom lighting manufacturer was presented in Childerhouse et al. (2002) to evaluate the product classification system proposed in Christopher and Towill (2000). The purpose of the system was to identify the appropriate process by which demand information was conveyed to the manufacturing floor and the coinciding demand chain strategy to be employed for a product as it moved through its PLC. The acronym DMV[3] was used to represent the parameters in the product classification system: duration of life cycle, time window for delivery, volume, variety, and variability. The research considered a classical PLC, shown in Figure 1.2, with five stages, where the maturity stage of Figure 1.2 was divided into two stages “maturity” and “saturation”. The research identified the following supply chain strategies for a product throughout its PLC: introduction stage – build to order, growth stage – MRP (agile), maturity stage – Kanban (lean), saturation stage – packing center (leagile), and decline – MRP (agile). The researchers found that by employing a different strategy at different PLC stages, the organization was focused on the correct product “order winner”, service level or cost, throughout the PLC. Aitken et al. (2003) provided an update to the case study in Childerhouse (2002) which included a flow diagram of the decision process used to determine when a product moved from stage to stage in its PLC.

A framework of supply chain management presented by Stadtler (2005) illustrated that supply chain management was built on a foundation of business functional areas, leading to the integration and coordination of supply chain partners to achieve a competitive advantage. Supply chain partners entered into a partnership expecting the relationship would result in a win-win situation over the life cycle of the product. With a single SCS for a product over its life cycle there were periods where one partner may achieve a financial benefit from another partner by utilizing a less than locally optimal strategy for the greater good of the supply chain. For these instances the supply chain should have methods to transfer or share the financial benefits between supply chain partners.

The purpose of Holmstrom et al. (2006) was to better understand how demand information could be used by organizations at different stages of the PLC. The researchers conducted a case study of a large manufacturer of durable consumer products. During the period prior to product introduction, planning and forecasting based on previous product launches was used to determine the production mix for the product. During the introduction stage of the PLC, point-of-sale or channel inventory data should be used to make adjustments to the product production mix. Once the product had reached the maturity stage of its PLC, demand information should be used to drive supply. During the decline phase, demand information should be used to develop plans to consume current in-process inventory in order to minimize the cost associated with obsolete inventory. The authors concluded that a supply chain should use demand information differently at different stages of the PLC, similar to Childerhouse et al. (2002).

Juttner et al. (2006) presented a case study to examine how the alignment of demand chain strategy and market segment could increase value over the life-cycle of a product. The case study considered a tobacco company that supplied the Eastern European market with cigarettes. The research found when the tobacco company aligned the manufacturing strategy of a product with that of the products market segment, value to the consumer was increased. An agile SCS should be employed for products with a large number of varieties and low volume, high value products, higher priced products, and products with a high degree of customization, and a lean SCS should be employed for products with a small number of varieties and high volume, low value products, and products with a high degree of standardization.

Seuring (2009) described a conceptual model proposing that a product's SCS was dependent upon the stage of the PLC and whether the product was part of a new or established supply chain. The framework described the three stages of the PLC as product design, production, and product return. The research supported the framework by examining six previously published cases.

Jeong (2011) presented an analytical model to identify the optimal inventory policy to minimize the total cost of deviations from targeted production rates and inventory levels of a product where demand followed the growth-maturity PLC. The growth-maturity PLC is similar to classical PLC; however, with the growth-maturity PLC expected demand remains essentially constant once it reaches the point of peak demand and there is no decline stage. The author considered a zero inventory policy and a production smoothing policy. Under the zero inventory policy, the model provided a function for the optimal time in the PLC to change from a make-to-stock to a make-to-order policy to minimize total cost deviation. When considering a production smoothing policy, the model provided the optimal production rate to minimize total cost deviation.

Hashemi et al. (2013) presented a structural equation model to examine the impact product design and product demand complexity had on the level of supply chain complexity. The paper discussed the model and the survey instrument only. The paper provided a discussion of previous frameworks for SCS selection and divided the characteristics considered into those that focused on demand aspects and those that focused on product design aspects. The purpose of the model was to provide insight to the extent to which product design and demand uncertainty impact supply chain strategy.

When considering the literature that recommended the SCS of a product should change during the PLC, a more accurate interpretation of the conclusions would be the method employed by the firm to convey demand information to the operations department should change during the PLC. The literature concluding the SCS of a product should be determined prior to market introduction considered supply chain management in a broader sense as the planning and management of information and material flow between organizations from raw materials to the end consumer. The concept that the SCS of a product should be determined prior to market introduction is an extension of the engineering principle, “design for manufacturing”, where consideration to the ease of manufacturability of a product is evaluated during the design stage of the product. The literature supports the concept of “design for SCM”, where the SCS of a product is considered during the design stage of the product to improve the flow of material and information throughout the supply chain over the life-cycle of the product.

2.5 Supply chain strategy selection and improvement

Several articles have used quantitative methods (e.g. mathematical programming, simulation modeling, etc.) to determine the combination of strategies that improved supply chain performance the most. Measures of supply chain performance that have been examined include optimizing multiple objectives considering profit, delivery lead time and promptness (Li and O’Brien, 1999; Li and O’Brien, 2001); delivery reliability, flexibility and responsiveness, cost, and assets (Wang et al., 2004); maximizing market responsiveness (Agarwal et al., 2006); customer service and cost (Goldsby et al., 2006); and minimizing the sum of supply chain and emissions costs (Besbes et al., 2012).

Li and O’Brien (1999) presented a multistage dynamic decision model to determine the combination of operational strategies to minimize the total dissatisfaction level of a three echelon supply chain. The dissatisfaction level was the weighted sum of the gaps between realized and target performance in four areas: profit, lead time, delivery promptness, and waste elimination. The model considered the operational strategies of make-to-order (lean SCS), make-from-stock (agile SCS), and make-to-stock (leagile SCS). The model was evaluated using an artificial data set. The researchers found that when the ordering lead time was shorter than the delivery lead time, an inventory buffer was needed. The location of the inventory buffer in the supply chain was modeled as a decoupling point between the supply chain strategies. The research demonstrated that for the scenarios presented, a combination of SCS minimized total dissatisfaction level.

Li and O'Brien (2001) presented a multiple objective optimization model to determine the SCS which resulted in the best performance when considering demand uncertainty and value-added capacity. The researchers considered three strategies and related each strategy to the strategies presented in Fisher (1997): manufacturing-to-order or MTO (lean SCS) described as physically efficient, manufacturing-from-stock or MFS (agile SCS) described as market responsive, and manufacturing-to-stock or MTS (leagile SCS) described as physically responsive. Supply chain performance was measured as the summation of the weighted gaps in achieving the objectives of three areas: profit, delivery lead time, and delivery promptness, with weights of 0.35, 0.35 and 0.30, respectively. Demand uncertainty was a factor used to determine the expected delivery delay and would have been better defined as supply uncertainty. The MTO strategy was modeled with no supply uncertainty in the supply chain. The MFS strategy was modeled with supply uncertainty only at the supplier and the MTS strategy was modeled with supply uncertainty at both the supplier and the production facility. Value-added capacity was the ratio of materials cost to finished product price. The authors considered fifteen combinations of supplier and production demand uncertainty at five levels of value-added capacity. The research demonstrated that the SCS which resulted in the best performance was dependent on the supplier uncertainty, production facility uncertainty and value-added capacity.

De Treville et al. (2004) drew upon previous published case studies to assert that a firm should focus on lead time reduction before information sharing to improve the responsiveness of a supply chain. The authors provided several propositions in support of their position. First was that demand information received after the start of production adds to transaction uncertainty. Second was that an improvement that reduced lead time was more likely to reduce transaction uncertainty than an improvement in information sharing. Third was that focusing on one area was more likely to reduce transaction uncertainty than focusing on both lead time reduction and information sharing simultaneously.

Wang et al. (2004) blended Huang et al. (2002) and Fisher (1997) with the SCOR framework developed by Supply Chain Council (SCC, 1999) in a multi-criteria decision-making model to assist practitioners with supplier selection dependent on product type and the objective of the supply chain. The researchers developed an analytic hierarchy process model based on the four categories of the SCOR framework: delivery reliability, flexibility and responsiveness, cost, and assets. The model was evaluated using artificial data for three products and three potential suppliers for each product. The evaluation of the model demonstrated the effectiveness of the SCOR framework in assisting practitioners with supplier selection: the supplier employing a lean SCS was selected for the functional product, the supplier with a leagile SCS was selected for the hybrid product, and the supplier with an agile SCS was selected for the innovative product.

The framework presented in Agarwal et al. (2006) assisted practitioners in determining the best SCS when performance of a supply chain was measured by its market responsiveness. The analytic network process developed by the authors considered supply chain attributes from four areas: market sensitiveness, information drivers, process integration, and flexibility. A group of experts were consulted to establish the relative importance between the attributes. Sensitivity analysis was completed varying the relative importance of the attributes, from 1/9 to 9, with all other terms held constant. The sensitivity analysis of lead time relative to cost showed that when greater importance was placed on cost than lead time, a lean SCS was appropriate. When the importance of cost and lead time were approximately equal then a leagile SCS was recommended, and when a greater importance was place on lead time compared to cost, then an agile SCS should be adopted. The research showed that even when market responsiveness was the objective of the supply chain, there were combinations of supply chain attributes and firm's objectives which could drive a firm to employ a SCS other than an agile SCS.

Goldsby et al. (2006) presented a simulation model of a three echelon supply chain to examine the customer service and cost impact of adopting an agile, a leagile, or a lean SCS. The supply chain consisted of a manufacturer, one or two distribution centers depending upon the strategy employed, and seven customers. The agile SCS was modeled with no finished goods inventory located at the distribution center or the manufacturer, one distribution center to serve all seven customers, and the manufacturer’s operational strategy was build-to-order. The leagile SCS was modeled with partially completed products inventoried at the two distribution centers and the manufacturer produced partially completed product based on forecasted demand. The lean SCS was modeled with finished inventory at the two distribution centers and the manufacturer produced completed product based on forecasted demand. The simulation showed that a lean SCS resulted in a higher level of customer service and had more total inventory in the supply chain than both the leagile SCS and agile SCS. As a result of how the agile SCS was modeled, with no finished goods inventory, sensitivity analysis showed that as the value of finished goods increased or as holding cost increased, an agile SCS resulted in a lower total supply chain cost.

The purpose of Hilletofth (2009) was to examine how firms employed operational strategies to develop differentiating SCS. The research presented case studies of a Swedish firm from the telecommunication industry and a Swedish firm from the appliance industry. The operational strategies of make-to-stock (MTS), deliver-to-order (DTO), assemble-to-order (ATO), sourcing-to-order (STO), and make-to-order (MTO) were considered. The article concluded the first step for identifying the appropriate SCS was to develop a product segmentation model based on geography, product type, and customer type. Then the appropriate combination of operational strategies should be selected by the firm to achieve a differentiated supply chain based on the firm’s understanding of the market and their ability to serve the market.

Besbes et al. (2012) presented a two phase modeling approach for supply chain member selection over the life-cycle of a product. The first phased included an analytic hierarchy process to determine the efficiency score of potential suppliers, production facilities, and distributors. The second phase was a multiple objective mathematical model to select the suppliers, producers, and distributors for each time period with an objective to minimize the summation of supply chain costs and carbon dioxide emission costs for all time periods. An example based on an actual supply chain was presented. The authors found when the supply chain utilized a different combination of suppliers, producers, and distributors for the introduction stage than for the maturity stage of the life-cycle, the total supply chain and carbon dioxide emission costs could be minimized. The article did not discuss the supply chain strategy of the various potential supply chain members.

2.6 Analytical models for supply chain strategy selection

Researchers have utilized analytical models to examine many areas of supply chain management. This section provides a brief survey of articles that consider analytical modeling to identify the appropriate SCS.

Herer et al. (2002) demonstrated with an analytical model how transshipment could be used as an inexpensive strategy to achieve a leagile supply chain. The research demonstrated mathematically that with transshipment a distribution network could reduce costs and improve service levels when compared to a distribution network without transshipment.

Kim and Ha (2003) developed an analytical model to determine the order quantity and the number of shipments for a single setup multiple delivery problem. The two echelon supply chain model included setup and inventory holding cost parameters for the seller, and ordering, inventory holding, and transportation cost parameters for the buyer.

A possible application for the model was for Kanban systems, where the number of shipments was the number of Kanban cards in the system.

Gupta and Benjaafar (2004) described a two stage analytical model of a make-to-order, make-to-stock, and decoupling point strategy to minimize the total inventory holding and backorder costs. A key parameter of the model was the capacity utilization of each stage. The analysis showed that when the capacity utilization of either stage was high, a make-to-stock strategy was more effective than a decoupling point strategy. When a decoupling strategy was employed, the strategy was more effective when those operations with higher capacity utilization were moved to the make-to-stock side of the supply chain.

Ahn and Kaminsky (2005) developed an analytical model to evaluate production and distribution policies of a two stage stochastic push-pull supply chain with an objective of total cost minimization. The supply chain was modeled so that the supply side followed a make-to-stock strategy and the demand side followed a make-to-order strategy. The model included costs associated with production, transportation, and inventory holding. The model assumed demand occurred according to a Poisson process. The authors derived a heuristic function for the economic order quantity that minimized total cost of the supply chain. The robustness of the heuristic was evaluated with a wide variety of parameters and the heuristic was found to be within 2% of the optimal solution.

Gupta and Benjaafar (2004) and Ahn and Kaminsky (2005) utilized analytical modeling to determine the best location of the decoupling point. Ernst and Kamrad (2000) demonstrated for supply chains with two customers a lean SCS was appropriate when the service level and demand uncertainty of the customers were similar, and an agile SCS should be employed when service levels and demand uncertainty of the customers differed greatly. Jeong (2011) presented an analytical model to identify the optimal inventory policy for a product where expected demand followed the growth-maturity PLC.

There has been limited research employing analytical modeling to examine SCS selection and the following gaps in the literature will be examined by this dissertation: (1) when a "misalignment" of SCS and product type might result in the best supply chain performance; (2) the appropriate SCS for a wide variety of supply chain structures and product/supply chain characteristics; and (3) the appropriate SCS over the life-cycle of a product.

2.7 Net present value and supply chain management

The net present value of supply chain costs should be determined to evaluate the value of the SCS over time (Kilbi et al., 2010). Guillen et al. (2005) developed a multiple objective stochastic model to determine the best supply chain network when the multiple objectives listed previously were considered. When designing a supply chain network under uncertainty to maximize expected profit, achieve a minimum service level, or minimize risk (the probability that expected profit falls below a targeted profit level) there are a large number of factors to consider. The first objective was to maximize the net present value of expect profit, where the net present value of costs to satisfy the demand and the revenue from the demand were incurred during the time period the demand was realized. A hypothetical case study was used to evaluate the model and identify the Pareto frontiers between the objectives.

To evaluate the cash flow impact of information sharing, Naim (2006) developed a net present value (NPV) spreadsheet simulation model. The author pointed out that although the literature had presented a number of measurements for supply chain performance, ultimately supply chain management decisions had monetary consequences and should incorporate cash flow analysis. The research included a cash flow equation as a function of time, where the profitability of the supply chain equaled the net present value of product revenue less the summation of variable cost and inventory holding cost; ordering cost was not considered. Three supply chains were considered to evaluate the impact of information sharing on cash flow: traditional – no information sharing, vendor managed inventory – the first two echelons had actual demand information, and e-commerce point of sale (EPOS) – demand information was shared with all echelons. Three ceteris paribus simulations were considered where each of the following variables was changed holding all others were constant: variable cost, holding cost, and cost of capital. Under all three simulations, the EPOS supply chain was superior to the other two supply chain strategies for all variable values considered, demonstrating the value of information sharing.

Franca et al. (2010) presented a multiple objective stochastic model which included the net present value of a supply chain's cash flows. The objective of the first stage of the model was to maximize expected profit and the objective of the second stage was to minimize supplier defects. The model did not consider lead time; therefore, all costs incurred to supply the product were incurred during the same time period as the demand. The model was evaluated using simulated data and the results showed that quality improvements had a positive impact on profit except when the defect rate was very high (greater than 100,000 per million). The Pareto frontier for a supply chain could provide critical information during supplier selection, as all suppliers with defect rates greater than this frontier should not be considered.

Disney et al. (2013) reformulated the classic economic production quantity (EPQ) model to incorporate NPV. When EPQ was evaluated considering the NPV of cash flow, no closed form solution could be determined for the optimal production quantity. The researchers used a Taylor Series to formulate an approximate total cost function and from the approximate total cost function the optimal production quantity could be determined. Scenario analysis was done to demonstrate that the percentage error of the approximate total cost function was within 2% of optimal cost and the accuracy of the approximate total cost function improved as the difference between the demand and production rates increased.

There has been a growing recognition in supply chain management literature that a more accurate valuation of supply chain costs should consider the timing of financial flows. Research that examines supply chain strategy selection and the NPV of financial flow is very limited. This dissertation addresses this gap in the literature.

2.8 Summary

The Fisher Model identified two supply chain strategies and two product types, where the SCS and product type should be aligned for SCM to be successful. Most researchers considered only two or three supply chain strategies to assess when each was the best. Many of the SCS frameworks that extended the Fisher Model acknowledge that there are at least three classifications of supply chain strategies: lean SCS, leagile SCS, and agile SCS. Three researchers presented frameworks that considered four supply chain strategies (Pagh and Cooper, 1998; Ernst and Kamrad, 2000; Lee, 2002); however, none consider the agilean SCS as described in this research. The agilean SCS, where the supply side employs a responsive strategy and the demand side employs a cost minimization strategy, can be an effective strategy to shorten the overall length of the supply chain while still benefiting from the cost advantage of the lean strategy when the majority of a product's costs are incurred late in the supply chain.

Many of the articles reviewed found a statistically significant relationship between supply chain performance and the alignment between SCS and demand characteristics. However, other researchers found that this was not true in all cases. This lack of generalizability of the alignment between SCS and demand characteristics is an area that this dissertation examines to provide managerial insights regarding the scenarios in which a misalignment of SCS and product type might minimize total NPV supply chain cost. There is a significant gap in the literature concerning the use of analytical models to assist practitioners with determining the appropriate SCS. This gap in the literature is the second area this dissertation examines by presenting a NPV analytical model of a multi-echelon supply chain to evaluate all four possible supply chain strategies, and the sensitivity of each SCS to operating and demand characteristics.

The most current literature examining supply chain strategies and product life-cycles suggested that the SCS of a product should be determined prior to market introduction during the design phase of the product. However, no research has provided a rigorous examination the circumstances when each type of SCS minimizes total cost over the entire PLC. In addition, no research has examined how a change in the length of the

PLC or the total expected demand impacts the SCS that minimizes total cost, nor has the research examined how the SCS of a product might best evolve during a PLC to minimize the impact to total cost. The third focal area of this dissertation addresses these gaps: (1) identifies the SCS that minimizes total NPV supply chain cost over the entire PLC, (2) provides managerial insight on how a change in the PLC length or the total expected demand might impact the SCS that minimizes total NPV supply chain cost over the entire PLC, and (3) presents a strategy to best evolve a supply chain from agile to lean to minimize the impact to total NPV supply chain cost over the entire PLC.

3. Analytical model

Analytical modeling is a valuable technique to examine the overall performance of a supply chain, providing strategic managerial insights as to how an objective (e.g. minimize total cost) is impacted as parameters and/or the relationship of parameters are varied. The benefits of analytical modeling can be furthered when probabilistic and uncertain attributes are incorporated into the model. A difficulty of analytical modeling is to describe the system in sufficient detail that useful results can be derived, but not in so much detail that managerial insights are lost in model complexity. A description of the notation used in this research is presented in Table 3.1.

3.1 Notation

Parameter	Description
$C(\cdot)$	General Total Cost function
$C_1(\cdot)$	Total Cost function when expected demand and demand forecast error are constant
$C_2(\cdot)$	Total Cost function when expected demand is a linear function of time and demand forecast error is constant
$C_3(\cdot)$	Total Cost function when expected demand mimics classical PLC and demand forecast error is an exponential decay function with respect to time
$C_{AA}(\cdot)$	Agile SCS Total Cost function
$C_{AL}(\cdot)$	Agilean SCS Total Cost function
$C_{LA}(\cdot)$	Leagile SCS Total Cost function
$C_{LL}(\cdot)$	Lean SCS Total Cost function
C_{SM}	Total net present value of supply side material cost function
C_{SI}	Total net present value of supply side inventory cost function
C_{SO}	Total net present value of supply side ordering cost function
C_{DM}	Total net present value of demand side production cost function
C_{DI}	Total net present value of demand side inventory cost function
C_{DO}	Total net present value of demand side ordering cost function
D_T	Total expected demand over the PLC
K_X	Purchased material cost per unit for supply chain strategy X
$L_{X,Y}$	Lead time for supply chain strategy X and supply chain side Y
M_X	Manufacturing cost per unit for supply chain strategy X
N_Y	Number of orders for supply chain side Y
N_{Y_q}	Number of orders for supply chain side Y of epoch q

N_Y^*	Optimal number of orders for supply chain side Y
O_Y	Order processing cost for supply chain side Y
$O_1(\cdot)$	Total net present value supply chain ordering cost for $C_1(\cdot)$
$P_1(\cdot)$	Total net present value supply chain production cost for $C_1(\cdot)$
Q	Number of epochs for the PLC
RMC	Relative manufacturing cost – the percentage of manufacturing costs to total production costs for a lean SCS
RMP	Ratio of manufacturing cost to purchased material cost – ratio of demand side manufacturing cost to supply side purchased material cost of a lean SCS
T	Duration in days of the forecast period
T_F	Duration in days of the PLC
T_Q	Length in days of each epoch
V	Net present value for a series of costs
$Z_{X,Y}$	Confidence interval factor for the service level for supply chain strategy X and supply chain side Y
$a_1, \ldots, a_5$	Constant terms for the PLC expected demand function
$d(t)$	Expected demand as a continuous function of time t
d_j	Expected discrete demand for day j
$\hat{d}(t)$	Actual demand as a continuous function of time t
$\hat{d}_j$	Actual discrete demand for day j
$\bar{d}$	Average demand for the forecast period $[0, T]$
$f(t)$	Demand forecast error as a continuous function of time t
f_j	Demand forecast error for day j
i	Cost of capital
j	Index of time in days
j_{n_Y}	Last day of order period n_Y for supply chain side Y
j_{q,n_Y}	Last day of order period n_Y for supply chain side Y of epoch q
q	Index of epochs
n_Y	Index of order periods for supply chain side Y from 1 to N_Y
n_{Y_q}	Index of order periods for supply chain side Y from 1 to N_Y of epoch q
t	Continuous time
x	Decay factor for demand forecast error
σ_j	Standard deviation of expected demand for day j
σ_{n_Y}	Standard deviation of the cumulative distribution function for order n_Y
α	Slope of the expected demand function over the length of the forecast period
β	Ratio of agile SCS purchased material unit cost to lean SCS purchased material unit cost
γ	Ratio of agile SCS manufacturing unit cost to lean SCS manufacturing unit cost
ρ	Half the probability range that $\hat{d}_j$ will be within f_j of d_j
τ	Attributes describing the number of orders and the costs per order
δ	Attributes describing demand and the forecast period
ψ	Attributes describing the SCS
Subscript	**Description**

S	A parameter associated with the supply side of the supply chain
D	A parameter associated with the demand side of the supply chain
A	An agile strategy parameter
L	A lean strategy parameter
X	A parameter dependent on the strategy type, (A or L)
Y	A parameter dependent on the side of the supply chain, (S or D)

Table 3.1: Parameters and coinciding description

The general total NPV supply chain cost model (Total Cost) is not specific to a particular SCS and is denoted without a subscript. When the model is specific to an agile SCS, an agilean SCS, a leagile SCS, or a lean SCS, the subscripts $AA, AL, LA,$ or LL are used to denote the SCS, respectively. A two letter subscript is used to identify the SCS of each side of the supply chain, with the supply side strategy denoted by the first subscript and the demand side strategy signified by the second subscript. The subscript X denotes a parameter that is dependent on the strategy type, so when the X is replaced by A, then an agile strategy or parameter is employed and when it is replaced by a L, then a lean strategy or parameter is adopted. The subscript Y signifies a parameter dependent on the side of the supply chain: when Y is replaced by S, it denotes a parameter associated with the supply side of the supply chain, and when the Y is replaced by D it signifies a parameter associated with the demand side of the supply chain.

3.2 Model description

The analytical cost model presented in this research is the summation of supply side and demand side NPV supply chain costs of a three echelon supply chain (supplier, manufacturer, and customer) with a decoupling point at the manufacturer and two inventory points as presented in Figure 3.1.

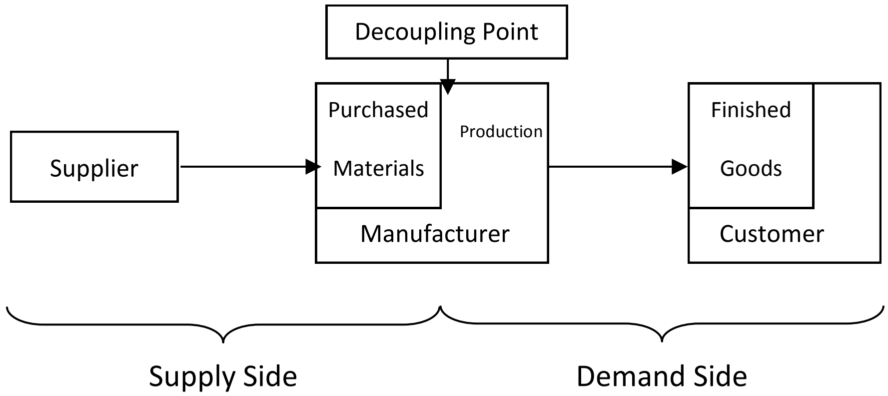


Figure 3.1: Three echelon supply chain with two inventory points

The model is developed with the following assumptions: 1) the managerial objective is minimizing total NPV supply chain cost, 2) the inventory replenishment system is periodic review, 3) expected demand d is a continuous function of time t, $d(t)$, 4) all transactions costs associated with an order are incurred at the time the order is placed, 5) all echelons are uncapacited, 6) there is a single product and a single channel, and 7) demand information is shared between all echelons.

Concerning the capacity assumption, it is assumed capacity is considered when supply chain members are chosen and those potential supply chain members where capacity is a constraining factor are not selected. The single product assumption follows frameworks reviewed in this research that are specific to product type (Fisher, 1997; Lamming et al., 2000; Lee, 2000; Ernst and Kamrad, 2002; Christopher and Towill, 2002; Huang et al., 2002; Randall et al., 2003; Cigolini et al., 2004; Wang et al., 2004). Firms may produce multiple products or multiple product families using multiple SCS, where the SCS employed for each product may differ depending on the product and demand characteristics associated with the product. Concerning the demand information sharing assumption, it has been shown that sharing demand information between supply chain members improves the performance of the supply chain (Gavirneni et al., 1999; Kim, 2000; Lee et al., 2000; Raghunathan, 2001; Aviv, 2001; Xu et al., 2001; Thonemann, 2002; Naim, 2006; Ouyang, 2007). However, the purpose of this research is not to determine the impact of demand information sharing on the appropriate SCS for a product. The material flow of the supply chain is from the supplier to the manufacturer; the manufacturer then transforms a unit of purchased material into a unit of finished goods, and the unit of finished goods is shipped from the manufacturer to the customer.

There are a number of objectives that a firm may adopt for evaluating the performance of a SCS, including but not limited to: maximize profit (Guillen et al., 2005;), minimize total cost (Kim and Ha, 2003; Ahn and Kaminsky, 2005; Naim, 2006), maximize responsiveness (Agarwal et al., 2006), minimize inventory cost (Gupta and Benjaafar, 2004), and minimize cost deviations (Jeong, 2011). Further, some research considered multiple objectives (Li and O'Brien, 1999; Li and O'Brien, 2001; Herer et al., 2002; Franca et al., 2010). Ultimately the adoption of a SCS has monetary consequences (Naim, 2006); therefore, this research focuses on the strategic objective of total NPV supply chain cost minimization.

The supply side costs include the purchased material unit cost K_X and order processing cost O_S. The demand side costs are the manufacturing unit cost M_X and order processing cost O_D. It is assumed that the supply chain members use either a traditional cost accounting system or an activity based cost accounting system, as the model will work with either cost accounting system. With a traditional cost accounting system, all overhead costs are allocated per unit based on expected demand and either labor hours or machine hours required per unit (Lin et al., 2001). With an activity based cost accounting system all overhead costs are traced to a product and are considered variable costs (Lin et al., 2001). With a traditional cost accounting system those costs typically associated with inventory holding cost are accounted for in the unit cost of the product (Grubbstrom, 1980).

The purchased material unit cost K_X is defined as all costs, including allocated overhead, incurred by the supply chain for the supplier to produce a unit of purchased material and transport it to the manufacturer, excluding ordering costs. The supply side ordering cost O_S includes all costs incurred by the supply chain for each order placed by the manufacturer to the supplier (e.g. order processing, machine setup, etc.), except for transportation cost which is included in K_X. Similarly, manufacturing unit cost M_X is defined as all costs, including allocated overhead, incurred by the supply chain for the manufacturer to transform a unit of purchased material into a unit of finished goods and transport it to the customer, excluding ordering costs. The demand side ordering cost O_D includes all costs incurred by the supply chain for each order placed by the customer to the manufacturer (e.g. order processing, machine setup, etc.), except for transportation cost which is included in M_X . With transportation cost included in the purchased material and manufacturing cost parameters, these parameters denote the delivered or landed cost per unit for each side of the supply chain.

The model considers a forecast period from time $t = 0$ to $t = T$, where T is a positive integer that defines the length of the forecast period in days. Continuous time is discretized such that j is an integer $[-\infty, T]$ reflecting one day of time. The model is developed for firms that employ a periodic review replenishment system. When a firm employs a periodic review replenishment system, the customer places N_D orders to the manufacturer, and the manufacturer places N_S orders to the supplier during the forecast period $[0, T]$. The set of possible values for N_D is taken as a positive integer $[1, T]$, such that $\frac{T}{N_D}$ is an integer. Therefore, the minimum value for N_D is 1 and the maximum value for N_D is T. The set of possible values for N_S is defined similarly so that $\frac{T}{N_S}$ is an integer. When T is a large number with many factors, the set of possible values for N_S and N_D may include many values. For example, when $T = 180$ the set includes $\{1, 2, 3, 4, 5, 6, 9, 10, 12, 15, 18, 20, 30, 36, 45, 60, 90, 180\}$. The individual orders from the customer to the manufacturer are indexed by $n_D = 0, 1, 2, \dots, N_D$ and the individual orders from the manufacturer to the supplier are indexed by $n_S = 0, 1, 2, \dots, N_S$. Order n_D is for the expected demand plus safety stock requirements for day $j_{n_D - 1} + 1$ to j_{n_D}, where j_{n_D} is given by

$$j_{n_D} = \frac{n_D T}{N_D}. \qquad \forall\, n_D = 0, 1, 2, \dots, N_D \quad (3.1)$$

Order n_D arrives at the customer at day $j_{n_D - 1}$. The length of each demand side order period in days is

$$\frac{T}{N_D}. \qquad (3.2)$$

Similarly, order n_S is for the expected demand plus safety stock requirements for day $j_{n_S - 1} + 1$ to j_{n_S} and it is scheduled to arrive at the manufacturer at day $j_{n_S - 1}$, where j_{n_S} is given by

$$j_{n_S} = \frac{n_S T}{N_S}. \qquad \forall\, n_S = 0, 1, 2, \dots, N_S \quad (3.3)$$

The length of each supply side order period in days is

$$\frac{T}{N_S}. \tag{3.4}$$

The purpose of the model is to capture the supply chain costs of a three echelon supply chain over a forecast period $[0, T]$. Expected demand can be viewed as a continuous function of time $d(t)$. Actual demand $\hat{d}(t)$ is assumed to be normally distributed about expected demand. The continuous expected demand and actual demand are discretized on a daily basis using equations (3.5) and (3.6), respectively.

$$d_j = \int_{j-1}^{j} d(t)\, dt \qquad \forall j = 1, 2, \dots, T \tag{3.5}$$

$$\hat{d}_j = \int_{j-1}^{j} \hat{d}(t)\, dt \qquad \forall j = 1, 2, \dots, T \tag{3.6}$$

The total expected demand for order period n_Y is

$$\sum_{j=j_{n_Y-1}+1}^{j_{n_Y}} d_j = \sum_{j=\frac{(n_Y-1)T}{N_Y}+1}^{\frac{n_Y T}{N_Y}} d_j. \tag{3.7}$$

The total expected demand for all N_D orders from the customer to the manufacturer during the forecast period $[0, T]$ is

$$\sum_{n_D=1}^{N_D} \sum_{j=\frac{(n_D-1)T}{N_D}+1}^{\frac{n_D T}{N_D}} d_j = \sum_{j=1}^{T} d_j. \tag{3.8}$$

The total expected demand for all N_S orders from the manufacturer to the supplier during the forecast period $[0, T]$ is

$$\sum_{n_S=1}^{N_S} \sum_{j=\frac{(n_S-1)T}{N_S}+1}^{\frac{n_S T}{N_S}} d_j = \sum_{j=1}^{T} d_j. \tag{3.9}$$

In this model, all transaction costs are assumed to be incurred at the time the order is placed, which is a reasonable assumption under most operational strategies with the exceptions of build-to-order and engineer-to-order. The research setting is where there is expected demand and it is reasonable to assume that at least some inventory exists in raw materials, work-in-process, and/or finished goods. Therefore, a portion, if not all, of the costs associated with fulfilling the order has already been realized. The demand side lead time, $L_{X,D}$, is the response time in days that the manufacturer requires to deliver an order to the customer and is dependent upon the demand side strategy employed. The time that the manufacturer receives order n_D is equal to the scheduled delivery time j_{n_D-1} minus the demand side lead time, $L_{X,D}$. Therefore, the demand side costs for order n_D are incurred at time

$$j_{n_D-1} - L_{X,D}. \tag{3.10}$$

This may be negative, which simply implies the manufacturer receives the order prior to the start of the forecast period.

The supply side lead time, $L_{X,S}$, is the response time in days that the supplier requires to deliver an order to the manufacturer and is dependent upon the supply side strategy adopted. The time that the supplier receives order n_S is equal to the scheduled delivery time j_{n_S-1} minus the summation of the demand side lead time, $L_{X,D}$, and the supply side lead time, $L_{X,S}$. Therefore, the supply side costs for order n_S are incurred at time

$$j_{n_S-1} - L_{X,D} - L_{X,S}. \tag{3.11}$$

This may be negative, which simply implies the supplier receives the order prior to the start of the forecast period.

Figure 3.2 illustrates the point in time when costs are incurred by the manufacturer and the supplier relative to order delivery time. This illustration assumes $T = 10;\ L_{X,D} = 2;\ L_{X,S} = 3;\ N_D = N_S = 2$. In this illustration the manufacturer receives order 1 at time -2 and order 2 at time 3, while the supplier receives order 1 at time -5 and order 2 at time zero.

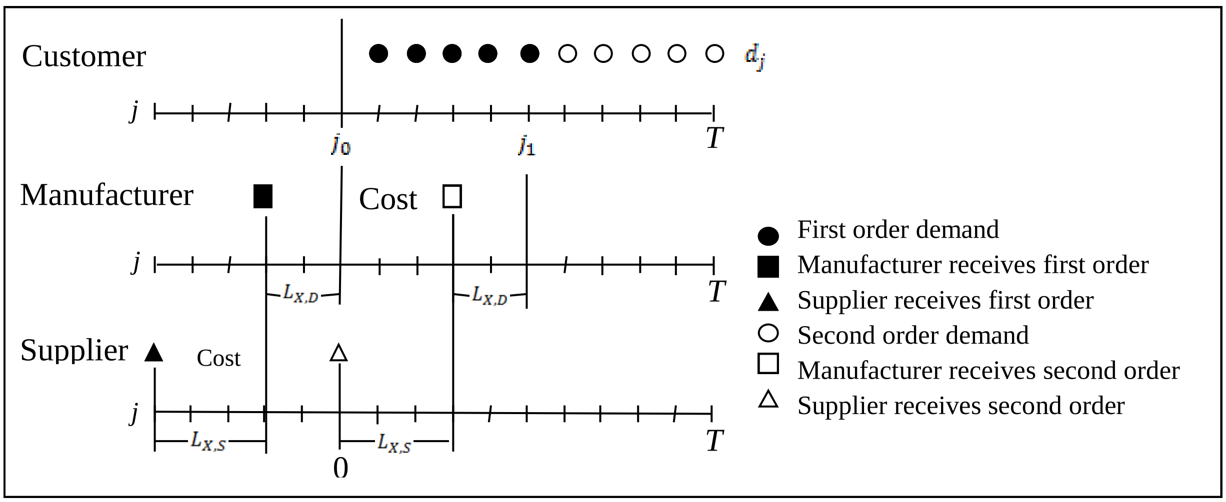


Figure 3.2: Timing of manufacturer and supplier costs relative to order delivery time

The demand side cost for order n_D includes the cost to manufacture and deliver the order quantity to the customer (based on the manufacturing cost for the demand side SCS, M_X), plus the order processing cost O_D. The supply side cost for order n_S includes the purchased material cost and the cost to deliver the order quantity to the manufacturer (based on the purchased material cost for the supply side SCS, K_X), plus the order processing cost O_S.

Fisher (1997) indicated the average forecast error of an innovative product is greater than 40% and the average forecast error for a functional product is 10% or less. However, the article did not provide a clear definition of average forecast error, a discussion of forecast error distribution, nor the length of time for which the average forecast error is calculated. Therefore, for this research demand forecast error at day j is assumed to be the absolute value of the difference between the expected demand, d_j, and the realized demand, $\hat{d}_j$, divided by d_j,

$$\frac{|d_j - \hat{d}_j|}{d_j}. \tag{3.12}$$

Although there are a number reasons for a forecast to be inaccurate, such as the forecast method, the ability of the forecaster, external factors, and demand variability, this research assumes that demand forecast error is the result of demand variability and that $\hat{d}_j$ can be approximated by a normal distribution about d_j with a variance of ${\sigma_j}^2$: $N\left[d_j, {\sigma_j}^2\right]$.

In this research the expected demand forecast error value f_j is the percentage of expected demand that defines a range that provides a 0.50 probability that the actual realized demand will be within f_j of the expected demand at time j, as shown in Figure 3.3.

$$P\left(d_j\left(1 - f_j\right) \leq \hat{d}_j \leq d_j\left(1 + f_j\right)\right) = 0.50. \tag{3.13}$$

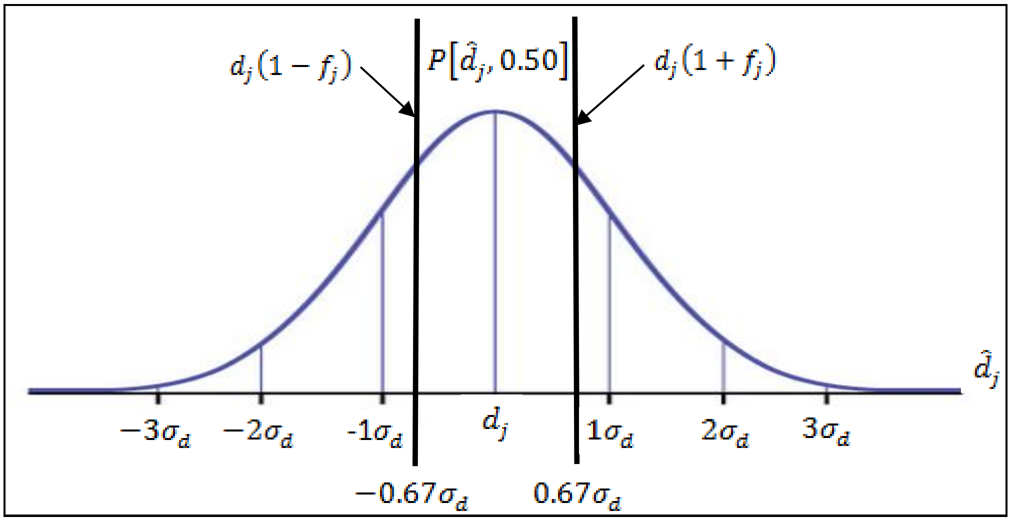


Figure 3.3: Actual demand normally distributed about expected demand

From equation 3.13, the probability that $\hat{d}_j$ is between d_j and $d_j(1+f_j)$ is 0.25. Therefore, the standard deviation of actual demand σ_j can be determined by solving the following equality,

$$d_j + Z_{0.25}\sigma_j = d_j + f_j d_j$$

$$d_j + 0.6745\sigma_j = d_j + f_j d_j,$$

$$\sigma_j = \frac{f_j * d_j}{0.6745}. \quad (3.14)$$

Other definitions of forecast error where ρ is the probability that actual demand differs from expected demand by no more than f_j can be calculated using

$$\sigma_j = \frac{f_j * d_j}{Z_\rho}. \quad (3.15)$$

The service level of a supply chain side is dependent upon the supply chain strategy for that side, denoted by $Z_{X,Y}$. The safety stock inventory level of each order period on either side of the supply chain depends on the service level associated with the strategy employed for that side of the supply chain, denoted by either $Z_{X,D}$ or $Z_{X,S}$, and the standard deviation of the cumulative distribution function (CDF) of demand for the order period n_D and n_S, σ_{n_D} and σ_{n_S}. It is assumed that the d_j demands are mutually independent. The standard deviation of the CDF for an order period is equal to the square root of the summation of the expected demand variances during the entire order period,

$$\sigma_{n_Y} = \sqrt{\sum_{j=j_{n_Y-1}+1}^{j_{n_Y}} \sigma_j{}^2}. \tag{3.16}$$

Therefore, the safety stock inventory levels for each order period, n_D and n_S, are

$$Z_{X,D}\sigma_{n_D} \tag{3.17}$$

and

$$Z_{X,S}\sigma_{n_S}. \tag{3.18}$$

The model assumes the initial safety stock inventory is zero for both sides of the supply chain, given by

$$Z_{X,Y}\sigma_0 = 0. \tag{3.19}$$

A portion of each order is for the change in safety stock inventory level. The change in safety stock inventory level from the previous order period to the next order period for the demand side and the supply side are determined as follows:

$$Z_{X,D}\left[\sigma_{n_D} - \sigma_{(n_D-1)}\right] \tag{3.20}$$

and

$$Z_{X,S}\left[\sigma_{n_S} - \sigma_{(n_S-1)}\right]. \quad (3.21)$$

When $N_D, N_S = 1$ there is only a single order placed for the entire forecast period; therefore, the total safety stock inventory requirement for the forecast period $[0, T]$ for the demand side and supply side is

$$Z_{X,Y}\sigma_1 = Z_{X,Y}\sqrt{\sum_{j=1}^{T} \sigma_j{}^2}. \quad (3.22)$$

To accurately assess the cost of a SCS the net present value (NPV), V, of supply chain costs should be determined (Kilbi et al., 2010). The net present value for a series of costs, $G_1, G_2, \dots, G_w$, (note: G_w denotes a generic cost term and does not represent a specific attribute) where cost G_w occurs at day j_w, and where i is the cost of capital per day is

$$V = \sum_{w=1}^{W} G_w e^{-ij_w} \quad (3.23)$$

The general analytical model used in this research consists of the NPV of six cost component functions: three to determine the total supply side cost and three to determine the total demand side cost. The six component functions and a description of each function are given in Table 3.2.

Equations	Function and description
3.7, 3.11, 3.23	$C_{SM} = K_X \left[\sum_{n_S=1}^{N_S} \left(\sum_{j=j_{n_S-1}+1}^{j_{n_S}} d_j\right) e^{-i\left(j_{n_S-1}-L_{X,S}-L_{X,D}\right)}\right]$
	Total expected supply side NPV purchased material cost for the forecast period $[0,T]$ for supply side SCS X.
3.11, 3.21, 3.23	$C_{SI} = K_X Z_{X,S} \left[\sum_{n_S=1}^{N_S} \left(\sigma_{n_S} - \sigma_{(n_S-1)}\right) e^{-i\left(j_{n_S-1}-L_{X,S}-L_{X,D}\right)}\right]$
	Total expected supply side NPV purchased material safety stock inventory cost for the forecast period $[0,T]$ for supply side SCS X.
3.11, 3.23	$C_{SO} = O_S \sum_{n_S=1}^{N_S} e^{-i\left(j_{n_S-1}-L_{X,S}-L_{X,D}\right)}$
	Supply side NPV order processing cost for the forecast period $[0,T]$ for supply side SCS X.
3.7, 3.10, 3.23	$C_{DM} = M_X \left[\sum_{n_D=1}^{N_D} \left(\sum_{j=j_{n_D-1}+1}^{j_{n_D}} d_j\right) e^{-i\left(j_{n_D-1}-L_{X,D}\right)}\right]$
	Total expected demand side NPV manufacturing cost for the forecast period $[0,T]$ for demand side SCS X.
3.10, 3.20, 3.23	$C_{DI} = M_X Z_{X,D} \left[\sum_{n_D=2}^{N_D} \left(\sigma_{n_D} - \sigma_{(n_D-1)}\right) e^{-i\left(j_{n_D-1}-L_{X,D}\right)}\right]$
	Total expected demand side NPV finished goods safety stock inventory cost for the forecast period $[0,T]$ for demand side SCS X.
3.10, 3.23	$C_{DO} = O_D \sum_{n_D=1}^{N_D} e^{-i\left(j_{n_D-1}-L_{X,D}\right)}$
	Demand side NPV order processing cost for the forecast period $[0,T]$ for demand side SCS X.

Table 3.2: Six cost component functions for the Total Cost

3.3 Model construction

The general analytical model for the Total Cost of a three echelon supply chain can be written as $C(\tau, \delta, \psi, i)$, a function of sets of parameters that describe (i) the ordering activities τ, (ii) the aspects of demand δ, (iii) the SCS ψ, and (iv) the cost of capital. The set τ includes those attributes that describe the number of orders and the cost per order: the number of supply side orders N_S; the number of demand side orders N_D; the supply side cost per order O_S; and the demand side cost per order O_D. Thus $\tau = [N_S, N_D, O_S, O_D]$. The set δ includes those attributes that describe expected demand during the forecast period: expected demand d_j; standard deviation of the CDF, σ_{n_D} and σ_{n_S}, as determined from the demand forecast error f_j, and the standard deviation of demand σ_j;

and the length of the forecast period T. Thus $\delta = [d_j, \sigma_{n_D}, \sigma_{n_S}, f_j, \sigma_j, T]$.The set ψ includes those attributes that describe the SCS: purchased material unit cost K_X; manufacturing unit cost M_X; supply side lead time $L_{X,S}$; demand side lead time $L_{X,D}$; supply side service level $Z_{X,S}$; and demand side service level $Z_{X,D}$. Thus $\psi = [K_X, M_X, L_{X,S}, L_{X,D}, Z_{X,S}, Z_{X,D}]$. The Total Cost also depends on the cost of capital, i. The cost of capital is more than the time value of money; it is also an implicit measurement of the risk associated with holding inventory. The risk of holding inventory is greater when the time value of money increases and when there is increased risk of spoilage or obsolescence associated with the product.

The general analytical model for the Total Cost of a three echelon supply chain is the sum of the six component functions presented in Table 3.2,

$$C(\tau, \delta, \psi, i) = C_{SM} + C_{SI} + C_{SO} + C_{DM} + C_{DI} + C_{DO} \qquad (3.24)$$

and in its expanded form

$$C(\tau, \delta, \psi, i) = K_X \left[\sum_{n_S=1}^{N_S} \left(\sum_{j=j_{n_S-1}+1}^{j_{n_S}} d_j\right) e^{-i\left(j_{n_S-1}-L_{X,S}-L_{X,D}\right)}\right] + K_X Z_{X,S} \left[\sum_{n_S=1}^{N_S} \left(\sigma_{n_S} - \sigma_{(n_S-1)}\right) e^{-i\left(j_{n_S-1}-L_{XS}-L_{XD}\right)}\right] + \sum_{n_S=1}^{N_S} O_S e^{-i\left(j_{n_S-1}-L_{X,S}-L_{X,D}\right)} + M_X \left[\sum_{n_D=1}^{N_D} \left(\sum_{j=j_{n_D-1}+1}^{j_{n_D}} d_j\right) e^{-i\left(j_{n_D-1}-L_{X,D}\right)}\right] + M_X Z_{X,D} \left[\sum_{n_D=2}^{N_D} \left(\sigma_{n_D} - \sigma_{(n_D-1)}\right) e^{-i\left(j_{n_D-1}-L_{XD}\right)}\right] + \sum_{n_D=1}^{N_D} O_D e^{-i\left(j_{n_D-1}-L_{X,D}\right)}. \qquad (3.25)$$

Simplification of equation (3.24) by factoring out common terms results in

$$C(\tau, \delta, \psi, i) =$$

$$e^{i(L_{X,S}+L_{X,D})}\left[\sum_{n_S=1}^{N_S}\left(K_X\left\{\left(\sum_{j=j_{n_S-1}+1}^{j_{n_S}} d_j\right) + Z_{X,S}\left(\sigma_{n_S} - \sigma_{(n_S-1)}\right)\right\} + O_S\right)e^{-i\left(j_{n_S-1}\right)}\right] +$$

$$e^{i(L_{X,D})}\left[\sum_{n_D=1}^{N_D}\left(M_X\left\{\left(\sum_{j=j_{n_D-1}+1}^{j_{n_D}} d_j\right) + Z_{X,D}\left(\sigma_{n_D} - \sigma_{(n_D-1)}\right)\right\} + O_D\right)e^{-i\left(j_{n_D-1}\right)}\right].$$

(3.26)

3.4 Supply chain strategy model construction

The four supply chain strategies in this research result from combining a lean and an agile strategy for the supply and demand side of the supply chain. Parameter values for the model were determined by mapping the cost and time attributes of efficient and responsive supply chains to a lean SCS and an agile SCS based on the primary purpose of the SCS. The primary purpose of a lean SCS is cost minimization; therefore, the cost attributes of a lean SCS are modeled with a lower cost per unit than in the agile SCS. The purchased material and manufacturing costs per unit for a lean SCS are K_L and M_L, respectively. The supply side lean index β is defined as the ratio of purchased material unit cost of an agile SCS to that of a lean SCS,

$$\beta = \frac{K_A}{K_L} > 1. \tag{3.27}$$

The demand side lean index γ is defined as the ratio of manufacturing unit cost of an agile SCS to that of a lean SCS,

$$\gamma = \frac{M_A}{M_L} > 1. \tag{3.28}$$

From equations (3.27) and (3.28), the purchased material cost per unit and manufacturing cost per unit for an agile SCS are βK_L and γM_L, accordingly, where $\beta, \gamma > 1$. The primary purpose of an agile SCS is responsiveness; therefore, the time attributes of an agile SCS are modeled as shorter than those of a lean SCS. It is assumed there are 360 days per year. This dissertation uses the description of a distant SCS and local SCS (Randall and Ulrich, 2001) as the basis for the supply side lead times and therefore assumes the supply side lead time of a lean SCS is $L_{L,S} = 60$ days and the supply side lead time for an agile SCS is $L_{A,S} = 7$ days. The demand side lead times are assumed to be $L_{L,D} = 21$ days for a lean SCS and $L_{A,D} = 3$ days for an agile SCS.

The stockout of a product may result from a number of events throughout a supply chain, such as forecasting error, variability in demand, lead time, manufacturing operations or human error. The combination of these events results in the average stockout rate of a supply chain. The service level of a supply chain is one minus the stockout rate. The service level of a lean supply chain is a market qualifier, meaning that the market expects a high level of service. The service level of an agile supply chain is a market winner, meaning that the service level of a supply chain could be the difference between not being awarded the business and being awarded the business (Agarwal et al., 2006). However, the market does not necessarily expect the service level of an agile SCS to be as high as a lean SCS. Fisher (1997) considers the average stockout rate of a product as a demand characteristic of the product; however, average stockout rate is more appropriately described as a characteristic of both the demand characteristics and the SCS employed for the product. Goldsby et al. (2006) demonstrated that because of the differing inventory policies of an agile SCS and a lean SCS, an agile SCS would result in a lower service level than a lean SCS. In this research, service level is modeled similarly in that the lean SCS has a higher service level than the agile SCS. However, the agile SCS is designed to respond much quicker to changes in demand because of the shorter lead times relative to the lean SCS. This research assumes that the stockout rate is the result of the inventory policy of the SCS for the product type and not an inherent characteristic of a product type. The service level of an agile SCS is modeled as 90% and the service level of a lean SCS is modeled as 98%. These correspond to the stockout rates of 10% and 2% for innovate and functional products from Fisher (1997), respectively. The corresponding $Z_{X,Y}$ values are 1.280 for an agile strategy and 2.055 for a lean strategy. Table 3.3 shows key parameter values for all four supply chain strategies used in this research.

		Agile	**Agilean**	**Leagile**	**Lean**
Supply Side	Purchased Material Cost	βK_L	βK_L	K_L	K_L
	$Z_{X,S}$	$Z_{A,S}$=1.280	$Z_{A,S}$=1.280	$Z_{L,S}$=2.055	$Z_{L,S}$=2.055
	$L_{X,S}$ (days)	$L_{A,S} = 7$	$L_{A,S} = 7$	$L_{L,S} = 60$	$L_{L,S} = 60$
Demand Side	Manufacturing Cost	γM_L	M_L	γM_L	M_L
	$Z_{X,D}$	$Z_{A,D}$=1.280	$Z_{L,D}$=2.055	$Z_{A,D}$=1.280	$Z_{L,D}$=2.055
	$L_{X,D}$ (days)	$L_{A,D} = 3$	$L_{L,D} = 21$	$L_{A,D} = 3$	$L_{L,D} = 21$

Table 3.3: Time and cost variables for a lean, leagile, and agile supply chain

The Total Cost function for an agile SCS from equation (3.26) and the values presented in Table 3.3 is

$$C_{AA}(\tau, \delta, \psi, i) =$$

$$e^{10i}\left[\sum_{n_S=1}^{N_S}\left(\beta K_L\left\{\left(\sum_{j=j_{n_S-1}+1}^{j_{n_S}} d_j\right) + 1.280\left(\sigma_{n_S} - \sigma_{(n_S-1)}\right)\right\} + O_S\right)e^{-i\left(j_{n_S-1}\right)}\right] +$$
$$e^{3i}\left[\sum_{n_D=1}^{N_D}\left(\gamma M_L\left\{\left(\sum_{j=j_{n_D-1}+1}^{j_{n_D}} d_j\right) + 1.280\left(\sigma_{n_D} - \sigma_{(n_D-1)}\right)\right\} + O_D\right)e^{-i\left(j_{n_D-1}\right)}\right]. \quad (3.29)$$

The Total Cost function for an agilean SCS from equation (3.26) and the values presented in Table 3.3 is

$$C_{AL}(\tau, \delta, \psi, i) =$$

$$e^{28i}\left[\sum_{n_S=1}^{N_S}\left(\beta K_L\left\{\left(\sum_{j=j_{n_S-1}+1}^{j_{n_S}} d_j\right) + 1.280\left(\sigma_{n_S} - \sigma_{(n_S-1)}\right)\right\} + O_S\right)e^{-i\left(j_{n_S-1}\right)}\right] +$$
$$e^{21i}\left[\sum_{n_D=1}^{N_D}\left(M_L\left\{\left(\sum_{j=j_{n_D-1}+1}^{j_{n_D}} d_j\right) + 2.055\left(\sigma_{n_D} - \sigma_{(n_D-1)}\right)\right\} + O_D\right)e^{-i\left(j_{n_D-1}\right)}\right]. \quad (3.30)$$

The Total Cost function for a leagile SCS from equation (3.26) and the values presented in Table 3.3 is

$$C_{LA}(\tau, \delta, \psi, i) =$$

$$e^{63i}\left[\sum_{n_S=1}^{N_S}\left(K_L\left\{\left(\sum_{j=j_{n_S-1}+1}^{j_{n_S}} d_j\right) + 2.055\left(\sigma_{n_S} - \sigma_{(n_S-1)}\right)\right\} + O_S\right)e^{-i\left(j_{n_S-1}\right)}\right] +$$
$$e^{3i}\left[\sum_{n_D=1}^{N_D}\left(\gamma M_L\left\{\left(\sum_{j=j_{n_D-1}+1}^{j_{n_D}} d_j\right) + 1.280\left(\sigma_{n_D} - \sigma_{(n_D-1)}\right)\right\} + O_D\right)e^{-i\left(j_{n_D-1}\right)}\right]. \quad (3.31)$$

The Total Cost function for a lean SCS from equation (3.26) and the values presented in Table 3.3 is

$$C_{LL}(\tau, \delta, \psi, i) =$$

$$e^{81i}\left[\sum_{n_S=1}^{N_S}\left(K_L\left\{\left(\sum_{j=j_{n_S-1}+1}^{j_{n_S}} d_j\right) + 2.055\left(\sigma_{n_S} - \sigma_{(n_S-1)}\right)\right\} + O_S\right) e^{-i\left(j_{n_S-1}\right)}\right] +$$

$$e^{21i}\left[\sum_{n_D=1}^{N_D}\left(M_L\left\{\left(\sum_{j=j_{n_D-1}+1}^{j_{n_D}} d_j\right) + 2.055\left(\sigma_{n_D} - \sigma_{(n_D-1)}\right)\right\} + O_D\right) e^{-i\left(j_{n_D-1}\right)}\right]. \quad (3.32)$$

3.5 Model analysis framework

To evaluate the impact supply chain and product characteristics have on SCS selection, this research identifies the SCS that results in lowest Total Cost while varying four key characteristics. The four key characteristics are: ratio of manufacturing cost to purchased material cost (*RMP*), demand forecast error, lean index and the cost of capital. *RMP* is defined as the ratio of demand side manufacturing cost of the lean SCS to the supply side purchased material cost of a lean SCS,

$$RMP = \frac{M_L}{K_L}. \quad (3.33)$$

RMP is similar to the value-added capacity characteristic considered by Li and O'Brien (2001), where the value-added capacity for a product is determined by the ratio of materials costs to finished product price. The *RMP* characteristic allows examination of how the location of where costs are incurred in a supply chain impacts SCS selection. When the lean index is small and *RMP* is less than 1, an agile SCS could result in a lower total supply chain cost than a lean SCS, because of the cost advantage of a shorter supply chain.

The model in this research uses the measurement of demand forecast error to define the level of demand uncertainty, as the value of demand forecast error increases as the level of demand uncertainty increases. According to the Fisher Model when demand uncertainty is high a product should be served with an agile SCS. The model in this research should demonstrate that as the demand forecast error increases the Total Cost of an agile SCS should decrease relative to a lean SCS.

The supply side lean index characteristic β is the ratio of purchased material cost for an agile SCS to a lean SCS, and the demand side lean index γ is the ratio of manufacturing cost for an agile SCS to a lean SCS. The main advantage of a lean SCS is the lower manufacturing and purchased material cost per unit; however, this advantage comes with the higher financial cost associated from incurring costs earlier as the result of the longer supply chain. If all parameters are equal, then with the longer supply chain the Total Cost of a lean SCS would be greater than that of an agile SCS. An agilean SCS and a leagile SCS would shorten the supply chain relative to a lean SCS, but both allow the supply chain to still realize a portion of the lower total production cost advantage of a lean SCS. For example, a supply chain may achieve a lower Total Cost relative to a lean SCS by adopting an agilean SCS when the majority of the product's costs are incurred late in the supply chain (high *RMP*). In this case, the shorter agilean SCS relative to a lean SCS would delay the point in time when supply side costs are incurred relative to a lean SCS, while an agilean SCS would realize the lower demand side manufacturing costs of the lean SCS, when all other terms are equal. For similar reasons, a leagile SCS may result in a lower Total Cost than a lean SCS when *RMP* is low. The advantage of the leagile SCS results from a shorter overall supply chain length than a lean SCS and delays the point in time when demand side and supply side costs are incurred relative to a lean SCS, when all other terms are equal.

The cost of capital (CoC) as defined for this research is more than just the time value of money, but also represents a measurement of the risk of holding inventory. The risk of holding inventory increases when a product is subject to spoilage or the probability of theft is high. This risk would also increase for those products in industries where technology uncertainty is high, such as the computer or electronics industry. Therefore, as the cost of capital increases, the cost advantage of the shorter agile SCS should increase.

To simulate a variety of possible supply chain scenarios, the research considers a low, medium, and high value for *RMP*, lean index, demand forecast error, and cost of capital. The low *RMP* value describes a supply chain where 90% of the total unit costs are in purchased material cost and 10% of the total unit costs are incurred at the manufacturer. The medium *RMP* value reflects a supply chain where supplier and manufacturer costs are equal. The high *RMP* value describes a supply chain where purchased material costs are 10% of the total unit costs and 90% of the total unit costs are incurred at the manufacturer. In practice, when a lean SCS provides a significant cost advantage compared to the other supply chain strategies and a firm chooses a strategy other than a lean SCS, then the firm's primary supply chain objective is most likely not total cost minimization. In those cases a model other than the one presented in this research should be employed to assist the firm in selecting the correct SCS. For this dissertation the model objective is cost minimization; therefore the lean index values considered are relatively low. The three values for demand forecast error are derived from the values Fisher (1997) used to describe the demand forecast error of a functional and innovative product and are similar to values used by Harrison et al., (2010): 10%, 40%, and 100%. In Fisher (1997) a demand forecast error of 10% or less described a supply chain with stable demand, and a demand forecast error between 40%-100% described a supply chain with unstable demand. The cost of capital is currently relatively low and has been for the last decade. Therefore, the low value of cost of capital is set at 5% annually (0.01389% per day) with medium and high values corresponding to increases of 5% annually. The model unit of time is days and it is assumed there are 360 days per year.

Characteristics	**Low**	**Medium**	**High**
RMP (M_L/K_L)	1/9	1	9
Cost of Capital (i)	0.01389%	0.02778%	0.04167%
Lean Index (β, γ)	1.01	1.02	1.04
Demand Forecast Error (f_j)	10%	40%	100%

Table 3.4: Characteristic values considered

Figure 3.4 illustrates the eighty-one possible scenarios considered in this research for the four characteristics given in Table 3.4 as separate cubes for each level of demand forecast error, when $\beta = \gamma$.

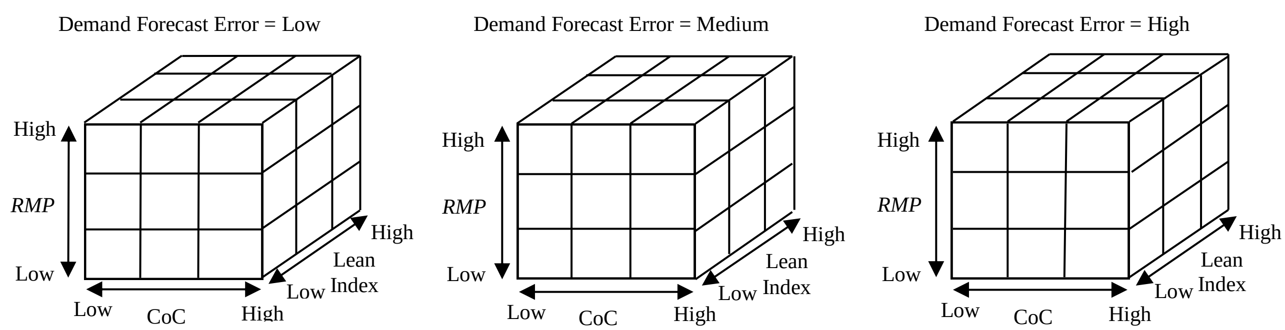


Figure 3.4: Scenario analysis considering *RMP*, lean index, demand forecast error, and cost of capital (CoC).

4. Examining the Fisher Model (lean and agile SCS only)

Question Q1 is addressed by this chapter: Under what circumstances does a supply chain with a misaligned SCS and product type outperform a supply chain with an aligned SCS and product type?

The primary purpose of this chapter is to identify the scenarios such that (i) the Total Cost of an agile SCS is lower than that of a lean SCS for a product with functional demand characteristics, and (ii) the Total Cost of a lean SCS is lower than that of an agile SCS for a product with innovative demand characteristics. The secondary purpose of this chapter is to examine the SCS, lean or agile, which a supply chain would move towards in response to changes in demand, product cost, lead time, and service level.

4.1 Problem description

This chapter considers the special case where expected demand and expected demand forecast error are constant for the forecast period $[0, T]$ and actual demand is normally distributed about expected demand, $\bar{d}$, during the forecast period: $N\left[\bar{d}, {\sigma_{\bar{d}}}^{2}\right]$. The expected demand rate for the forecast period $[0, T]$ is

$$\bar{d} = \frac{\int_0^T d(t)dt}{T}. \qquad (4.1)$$

With time measured in days, d_j is daily expected demand and

$$d_j = \bar{d}. \qquad \forall\, j = 1, 2, \dots, T \quad (4.2)$$

With expected demand forecast error constant for the forecast period,

$$f_j = f. \qquad \forall\, j = 1, 2, \dots, T \quad (4.3)$$

The standard deviation of actual daily demand about expected demand when both expected demand and demand forecast error are constant for the forecast period is defined by substituting equations (4.1) and (4.2) into equation (3.14),

$$\sigma_j = \frac{f * \bar{d}}{0.6745}. \qquad \forall\, j = 1, 2, \ldots, T \quad (4.4)$$

The standard deviation of daily demand is constant for the forecast period and the daily expected demands are assumed mutually independent. Therefore, the standard deviation of demand over the order period for each side of the supply chain is the product of σ_j and the square root of the length of each order period. From equation (3.16), the standard deviation of demand for every demand side order period is

$$\sigma_{n_D} = \sqrt{\sum_{j=j_{n_D-1}+1}^{j_{n_D}} {\sigma_j}^2} = \frac{f * \bar{d}}{0.6745}\sqrt{\frac{T}{N_D}}. \qquad \forall\, n_D = 1, 2, \ldots, N_D \quad (4.5)$$

From equation (3.16), the standard deviation of demand for every supply side order period is

$$\sigma_{n_S} = \sqrt{\sum_{j=j_{n_S-1}+1}^{j_{n_S}} {\sigma_j}^2} = \frac{f * \bar{d}}{0.6745}\sqrt{\frac{T}{N_S}}. \qquad \forall\, n_S = 1, 2, \ldots, N_S \quad (4.6)$$

When expected demand and demand forecast error are constant for the forecast period, the change in safety stock inventory level from period to period, given by equations (3.20) and (3.21), is zero for both inventory locations (manufacturer and customer) and only the safety stock level for the first order period needs to be determined.

The Total Cost function when expected demand and demand forecast error are constant, $C_1(\tau, \delta, \psi, i)$, is determined by substituting equations (4.2), (4.3), (4.5), and (4.6) into equation (3.26),

$$C_1(\tau, \delta, \psi, i) = e^{i(L_{X,S}+L_{X,D})}\left[\sum_{n_S=1}^{N_S}\left(K_X\left\{\left(\sum_{j=j_{n_S-1}+1}^{j_{n_S}}\bar{d}\right) + Z_{X,S}\sigma_1\right\} + O_S\right)e^{-i\left(j_{n_S-1}\right)}\right] + e^{i(L_{X,D})}\left[\sum_{n_D=1}^{N_D}\left(M_X\left\{\left(\sum_{j=j_{n_D-1}+1}^{j_{n_D}}\bar{d}\right) + Z_{X,D}\sigma_1\right\} + O_D\right)e^{-i\left(j_{n_D-1}\right)}\right]. \tag{4.7}$$

The summations $\sum_{j=j_{n_D-1}+1}^{j_{n_D}}\bar{d}$ and $\sum_{j=j_{(n_S-1)}+1}^{j_{n_S}}\bar{d}$ in equation (4.7), are the total expected demand during a demand side and supply side order period, respectively. The total expected demand for every demand side order period is the product of the length of the demand side order period, equation (3.2), and expected daily demand $\bar{d}$,

$$\sum_{j=j_{n_D-1}+1}^{j_{n_D}}\bar{d} = \frac{\bar{d}T}{N_D}. \tag{4.8}$$

The total expected demand for every supply side order period is the product of the length of the order period, equation (3.4), and expected daily demand $\bar{d}$,

$$\sum_{j=j_{n_S-1}+1}^{j_{n_S}}\bar{d} = \frac{\bar{d}T}{N_S}. \tag{4.9}$$

The Total Cost function $C_1(\tau, \delta, \psi, i)$ can be simplified further by substituting equations (3.1), (3.3), (4.8) and (4.9) into equation (4.7),

$$C_1(\tau, \delta, \psi, i) =$$

$$e^{i(L_{X,S}+L_{X,D})}\left(K_X\left[\sum_{n_S=1}^{N_S}\frac{\bar{d}T}{N_S}\ e^{-i\frac{T}{N_S}(n_S-1)} + Z_{X,S}\sigma_1\right] + O_S\sum_{n_S=1}^{N_S} e^{-i\frac{T}{N_S}(n_S-1)}\right) +$$

$$e^{i(L_{X,D})}\left(M_X\left[\sum_{n_D=1}^{N_D}\frac{\bar{d}T}{N_D} e^{-i\frac{T}{N_D}(n_D-1)} + Z_{X,D}\sigma_1\right] + O_D\sum_{n_D=1}^{N_D} e^{-i\frac{T}{N_D}(n_D-1)}\right). \quad (4.10)$$

Each summation in equation (4.7) is a partial sum of a geometric series with the general form

$$a + ar + ar^2 + \cdots + ar^{m-1} + \cdots \text{ where } a \neq 0. \quad (4.11)$$

Riddle (1979) described the partial sum (s_M) for the first *m* terms of a geometric series where $r \neq 1$ as

$$s_M = \frac{a(1-r^m)}{(1-r)}. \quad (4.12)$$

The value of $a, r,$ and m for the series $\sum_{n_S=1}^{N_S}\frac{\bar{d}T}{N_S}\ e^{-i\frac{T}{N_S}(n_S-1)}$ are $a = \frac{\bar{d}T}{N_S}$, $r = e^{-i\frac{T}{N_S}}$, and $m = N_S$ and the partial sum of the geometric series is

$$\sum_{n_S=1}^{N_S}\frac{\bar{d}T}{N_S}\ e^{-i\frac{T}{N_S}(n_S-1)} = \frac{a(1-r^m)}{(1-r)} = \frac{\bar{d}T\left(1-\left(e^{-i\frac{T}{N_S}}\right)^{N_S}\right)}{N_S\left(1-e^{-i\frac{T}{N_S}}\right)} = \frac{\bar{d}T\left(1-e^{-iT}\right)}{N_S\left(1-e^{\frac{-iT}{N_S}}\right)}. \quad (4.13)$$

Using the same technique to transform the remaining three summations in equation (4.7) and factoring out common terms results in the following Total Cost function when expected demand and forecast error are constant for the forecast period $[0, T]$,

$$C_1(\tau, \delta, \psi, i) = e^{i(L_{X,S}+L_{X,D})}\left[K_X\bar{d}\left(\frac{T(1-e^{-iT})}{N_S\left(1-e^{\frac{-iT}{N_S}}\right)} + \frac{z_{X,S}f}{0.6745}\sqrt{\frac{T}{N_S}}\right) + O_S\frac{(1-e^{-iT})}{\left(1-e^{\frac{-iT}{N_S}}\right)}\right] +$$

$$e^{i(L_{X,D})}\left[M_X\bar{d}\left(\frac{T(1-e^{-iT})}{N_D\left(1-e^{\frac{-iT}{N_D}}\right)} + \frac{z_{X,D}f}{0.6745}\sqrt{\frac{T}{N_D}}\right) + O_D\frac{(1-e^{-iT})}{\left(1-e^{\frac{-iT}{N_D}}\right)}\right]. \quad (4.14)$$

Let $u_T = \frac{(1-e^{-iT})}{\left(1-e^{\frac{-iT}{N_S}}\right)}$ and $v_T = \frac{(1-e^{-iT})}{\left(1-e^{\frac{-iT}{N_D}}\right)}$, therefore

$$C_1(\tau, \delta, \psi, i) =$$

$$e^{i(L_{X,S}+L_{X,D})}\left[K_X\bar{d}\left(\frac{Tu_T}{N_S} + \frac{z_{X,S}f}{0.6745}\sqrt{\frac{T}{N_S}}\right) + O_S u_T\right] +$$

$$e^{i(L_{X,D})}\left[M_X\bar{d}\left(\frac{Tv_T}{N_D} + \frac{z_{X,D}f}{0.6745}\sqrt{\frac{T}{N_D}}\right) + O_D v_T\right]. \quad (4.15)$$

In the simplest terms, $C_1(\tau, \delta, \psi, i)$ is the sum of the total NPV supply chain production cost, $P_1(\tau, \delta, \psi, i)$, and the total NPV supply chain order processing cost, $O_1(\tau, \delta, i)$. The total NPV supply chain production cost is

$$P_1(\tau, \delta, \psi, i) = \bar{d}e^{i(L_{X,D})}\left[K_X e^{i(L_{XS})}\left(\frac{Tu_T}{N_S} + \frac{z_{X,S}f}{0.6745}\sqrt{\frac{T}{N_S}}\right) + M_X\left(\frac{Tv_T}{N_D} + \frac{z_{X,D}f}{0.6745}\sqrt{\frac{T}{N_D}}\right)\right], \quad (4.16)$$

where the first term is the total NPV supply side production cost

$$P_{1_S} = \bar{d}e^{i(L_{X,S}+L_{X,D})}K_X\left(\frac{Tu_T}{N_S} + \frac{z_{X,S}f}{0.6745}\sqrt{\frac{T}{N_S}}\right) \quad (4.17)$$

and the second term is the total NPV demand side production cost

$$P_{1_D} = \bar{d}e^{i(L_{X,D})}M_X\left(\frac{Tv_T}{N_D} + \frac{z_{X,D}f}{0.6745}\sqrt{\frac{T}{N_D}}\right). \quad (4.18)$$

The total NPV supply chain order processing cost is

$$O_1(\tau, \delta, i) = e^{i(L_{X,D})}\left[e^{i(L_{XS})}O_S u_T + O_D v_T\right], \quad (4.19)$$

where the first term is the total NPV supply side order processing cost

$$O_{1_S} = O_S u_T e^{i(L_{X,S}+L_{X,D})} \quad (4.20)$$

and the second term is total NPV demand side order processing cost

$$O_{1_D} = O_D v_T e^{i(L_{X,D})}. \quad (4.21)$$

$P_1(\tau, \delta, \psi, i)$ and $O_1(\tau, \delta, i)$ are supply chain cost components dependent upon the number of order periods, N_S and N_D; as N_S and N_D increases, with all other terms held constant, $P_1(\tau, \delta, \psi, i)$ decreases and $O_1(\tau, \delta, i)$ increases. If $C_1(\tau, \delta, \psi, i)$ is a convex function, then there are values for N_S and N_D that minimize $C_1(\tau, \delta, \psi, i)$; N_S^* and N_D^* respectively. The values for N_S^* and N_D^* are positive integers $[1, T]$.

H1: When demand is constant there are values for the number of ordering periods, N_S^* and N_D^*, which minimize $C_1(\tau, \delta, \psi, i)$ for the forecast period $[0, T]$.

Proof: $C_1(\tau, \delta, \psi, i)$ is a convex function if $P_1(\tau, \delta, \psi, i)$ decreases at a decreasing rate and $O_1(\tau, \delta, i)$ increases at an increasing rate as the value for N_S^* and N_D^* increases.

Step 1: $P_1(\tau, \delta, \psi, i)$ decreases at a decreasing rate as N_S or N_D increases for $K_X, M_X, \bar{d}, i, L_{X,S}, L_{X,D}, T, f, N_S, N_D > 0$.

The function $P_1(\tau, \delta, \psi, i)$ is such that if P_{1_S} decreases at a decreasing rate with respect to N_S, then P_{1_D} must decrease at a decreasing rate with respect to N_D. Therefore, the following proof only examines P_{1_S}. P_{1_S} decreases at a decreasing rate with respect to N_S for all values of $N_S = 1, 2, \ldots, T$ when $P_{1_S}{}' < 0$ and $P_{1_S}{}'' > 0$.

$$P_{1_S} = \bar{d}e^{i(L_{X,S}+L_{X,D})}K_X\left(\frac{T}{N_S}\frac{(1-e^{-iT})}{\left(1-e^{\frac{-iT}{N_S}}\right)} + \frac{Z_{X,S}f}{0.6745}\sqrt{\frac{T}{N_S}}\right)$$

$$P_{1_S}{}' =$$

$$\bar{d}e^{i(L_{X,S}+L_{X,D})}TK_X\left(1-e^{-iT}\right)\left(\frac{d}{dN_S}\frac{1}{N_S\left(1-e^{\frac{-iT}{N_S}}\right)}\right) + \bar{d}e^{i(L_{XS}+L_{XD})}\frac{K_X Z_{X,S} f\sqrt{T}}{0.6745}\left(\frac{d}{dN_S}\sqrt{\frac{1}{N_S}}\right)$$

$$P_{1_S}{}' =$$

$$\left[\bar{d}e^{i(L_{X,S}+L_{X,D})}TK_X\left(1-e^{-iT}\right)\right]\left[\frac{iTe^{\frac{-iT}{N_S}} - N_S\left(1-e^{\frac{-iT}{N_S}}\right)}{N_S{}^3\left(1-e^{\frac{-iT}{N_S}}\right)^2}\right] + \left[\bar{d}e^{i(L_{X,S}+L_{X,D})}\frac{K_X Z_{X,S} f\sqrt{T}}{1.349}\right]\left[\frac{-1}{N_S\sqrt{N_S}}\right]$$

The value of $P_{1_S}{}'$ is the sum of two terms that are each the product of a positive term and a negative term; hence, the sum of two negative terms must always be less than zero, for $K_X, \bar{d}, i, L_{X,S}, L_{X,D}, T, f, N_S > 0$,

$$P_{1_S}{}' = [+][-] + [+][-] < 0.$$

$$P_{1_S}'' = \bar{d}e^{i(L_{X,S}+L_{X,D})}TK_X(1-e^{-iT})\left(\frac{d}{dN_S}\frac{iTe^{\frac{-iT}{N_S}}}{N_S{}^3\left(1-e^{\frac{-iT}{N_S}}\right)^2}+\frac{d}{dN_S}\frac{-N_S}{N_S{}^3\left(1-e^{\frac{-iT}{N_S}}\right)^2}+\right.$$

$$\left.\frac{d}{dN_S}\frac{N_S e^{\frac{-iT}{N_S}}}{N_S{}^3\left(1-e^{\frac{-iT}{N_S}}\right)^2}\right)+\bar{d}e^{i(L_{X,S}+L_{X,D})}\frac{K_X Z_{X,S} f\sqrt{T}}{1.349}\left(\frac{d}{dN_S}\frac{-1}{N_S\sqrt{N_S}}\right)$$

$$P_{1_S}'' = \bar{d}e^{i(L_{X,S}+L_{X,D})}TK(1-e^{-iT})$$

$$\left(\frac{iTe^{\frac{-iT}{N_S}}\left(iT\left(1-e^{\frac{-iT}{N_S}}\right)-3N_S\left(1-e^{\frac{-iT}{N_S}}\right)+2iT\right)+2N_S{}^2\left(1-e^{\frac{-iT}{N_S}}\right)-2iTN_Se^{\frac{-iT}{N_S}}+e^{\frac{-iT}{N_S}}\left(iTN_S\left(1-e^{\frac{-iT}{N_S}}\right)-2N_S{}^2\left(1-e^{\frac{-iT}{N_S}}\right)+2iTN_S\right)}{N_S{}^5\left(1-e^{\frac{-iT}{N_S}}\right)^3}\right)+$$

$$\bar{d}e^{i(L_{XS}+L_{XD})}K_X Z_{X,S} f\sqrt{T}\left(\frac{1.1119}{N_S{}^2\sqrt{N_S}}\right)$$

$$P_{1_S}'' = \left[\bar{d}e^{i(L_{X,S}+L_{X,D})}K_X T(1-e^{-iT})\right]\left[\frac{2N_S{}^2\left(1-e^{\frac{-iT}{N_S}}\right)^2-2iTN_Se^{\frac{-iT}{N_S}}\left(1-e^{\frac{-iT}{N_S}}\right)+i^2T^2e^{\frac{-iT}{N_S}}\left(3-e^{\frac{-iT}{N_S}}\right)}{N_S{}^5\left(1-e^{\frac{-iT}{N_S}}\right)^3}\right]+$$

$$\left[\bar{d}e^{i(L_{X,S}+L_{X,D})}K_X Z_{X,S} f\sqrt{T}\right]\left[\frac{1.1119}{N_S{}^2\sqrt{N_S}}\right]$$

The value of P_{1_S}'' is the sum of two terms that are each the product of a two positive terms; hence, the sum of two positive terms must always be greater than zero, subject to $K_X, \bar{d}, i, L_{X,S}, L_{X,D}, T, f, N_S > 0$,

$$P_{1_S}'' = [+][+] + [+][+] > 0.$$

From *Step 1*, $P_{1_S}' < 0$ and $P_{1_S}'' > 0$ for all values of $N_S = 1, 2, \dots, T$; therefore, P_{1_S} decreases at a decreasing rate for all values of $N_S = 1, 2, \dots, T$. From similar reasoning, P_{1_D} for all values of $N_D = 1, 2, \dots, T$ must also decrease at a decreasing rate.

Therefore, *Step 1* is accepted: $P_1(\tau, \delta, \psi, i)$ decreases at a decreasing rate as N_S or N_D increases for $K_X, M_X, \bar{d}, i, L_{X,S}, L_{X,D}, T, f, N_S, N_D > 0$. The limit of $P_1(\tau, \delta, \psi, i)$ as $N_S \text{ and } N_D \rightarrow T$ establishes the lower bound for the total NPV supply chain production cost as

$$\lim_{N_S \text{ and } N_D \rightarrow T} P_1(\tau, \delta, \psi, i) = \bar{d}e^{i(L_{X,D})}\left[K_X e^{i(L_{X,S})}\left(\frac{(1-e^{-iT})}{(1-e^{-i})} + \frac{Z_{XS}f}{0.6745}\right) + M_X\left(\frac{(1-e^{-iT})}{(1-e^{-i})} + \frac{Z_{X,D}f}{0.6745}\right)\right]. \quad (4.22)$$

The upper bound for the total NPV supply chain production cost is when N_S and N_D both equal one and is

$$P_1(\tau, \delta, \psi, i) = \bar{d}Te^{i(L_{X,D})}\left[K_X e^{i(L_{X,S})}\left(1 + \frac{Z_{X,S}f}{0.6745\sqrt{T}}\right) + M_X\left(1 + \frac{Z_{X,D}f}{0.6745\sqrt{T}}\right)\right]. \quad (4.23)$$

Step 2: $O_1(\tau, \delta, i)$ increases as an increasing rate as N_S or N_D increases for $O_S, O_D, i, L_{X,S}, L_{X,D}, T, N_S, N_D > 0$.

The function $O_1(\tau, \delta, i)$ is such that if O_{1_S} increases at an increasing rate with respect to N_S, then O_{1_D} must increase at an increasing rate with respect to N_D. Therefore, the following proof only examines O_{1_S}. O_{1_S} increases at an increasing rate with respect to N_S for all values of $N_S = 1, 2, \ldots, T$ when $O_{1_S}{}' > 0$ and $O_{1_S}{}'' > 0$.

$$O_{1_S} = O_S e^{i(L_{X,S}+L_{X,D})} \frac{(1-e^{-iT})}{\left(1-e^{\frac{-iT}{N_S}}\right)}$$

$$O_{1_S}{}' = O_S e^{i(L_{X,S}+L_{X,D})}(1-e^{-iT})\left(\frac{d}{dN_S}\frac{1}{\left(1-e^{\frac{-iT}{N_S}}\right)}\right)$$

$$O_{1_S}{}' = \left[O_S e^{i(L_{X,S}+L_{X,D})}(1-e^{-iT})\right]\left[\frac{iTe^{\frac{-iT}{N_S}}}{N_S{}^2\left(1-e^{\frac{-iT}{N_S}}\right)^2}\right]$$

The value of $O_{1_S}{}'$ is the product of a two positive terms; therefore, it must always be greater than zero, for $O_S, i, L_{X,S}, L_{X,D}, T, N_S > 0$,

$$O_{1_S}{}' = [+][+] > 0.$$

$$O_{1_S}{}'' = O_S iTe^{i(L_{X,S}+L_{X,D})}(1-e^{-iT})\left(\frac{d}{dN_S}\frac{e^{\frac{-iT}{N_S}}}{N_S{}^2\left(1-e^{\frac{-iT}{N_S}}\right)^2}\right)$$

$$O_{1_S}{}'' = \left[O_S iTe^{i(L_{X,S}+L_{X,D})}(1-e^{-iT})\right]\left[\frac{iTe^{\frac{-iT}{N_S}}\left(1+e^{\frac{-iT}{N_S}}\right)-2N_S e^{\frac{-iT}{N_S}}\left(1-e^{\frac{-iT}{N_S}}\right)}{N_S{}^4\left(1-e^{\frac{-iT}{N_S}}\right)^3}\right]$$

The value of $O_{1_S}{}''$ is the product of a two positive terms; therefore, it must always be greater than zero, for $O_S, i, L_{X,S}, L_{X,D}, T, N_S > 0$,

$$O_{1_S}{}'' = [+][+] > 0.$$

From *Step 2*, $O_{1_S}{}' > 0$ and $O_{1_S}{}'' > 0$ for all values of $N_S = 1, 2, \ldots, T$; therefore, O_{1_S} increases at an increasing rate for all values of $N_S = 1, 2, \ldots, T$. From similar reasoning, O_{1_D} for all values of $N_D = 1, 2, \ldots, T$ must also increase at an increasing rate. Therefore, *Step 2* is accepted: $O_1(\tau, \delta, i)$ increases at an increasing rate as N_S or N_D increases for $O_S, O_D, i, L_{X,S}, L_{X,D}, T, N_S, N_D > 0$. The limit of $O_1(\tau, \delta, i)$ as N_S and $N_D \rightarrow T$ defines the upper bound of the total NPV supply chain order processing cost as

$$\lim_{N_S \text{ and } N_D \to T} O_1(\tau, \delta, i) = \frac{e^{i(L_{XD})}(1-e^{-iT})}{(1-e^{-i})}\left(O_S e^{i(L_{X,S})} + O_D\right). \tag{4.24}$$

The lower bound for the total NPV supply chain order processing cost is when N_S and N_D both equal one and is

$$O_1(\tau, \delta, i) = e^{i(L_{X,D})}\left(e^{i(L_{XS})} O_S + O_D\right). \tag{4.25}$$

Step 1 and *Step 2* together provide the *Proof*: $C_1(\tau, \delta, \psi, i)$ is a convex function with $P_1(\tau, \delta, \psi, i)$ decreasing at a decreasing rate and $O_1(\tau, \delta, i)$ increasing at an increasing rate as the value for N_S^* and N_D^* increases; therefore, *H1* is accepted.

The first derivative of $C_1(\tau, \delta, \psi, i)$ with respect to N_S is

$$\frac{d}{dN_S} C_{SCS1}(\tau, \delta, \psi, i) = {P_{1_S}}' + {O_{1_S}}' \tag{4.26}$$

The result of equation (4.26) set equal to zero and simplified is

$$0 = \frac{O_S i}{K\bar{d}} + 1 + \frac{iT}{N_S} - 0.74129 Z_{X,S} f \sqrt{\frac{N_S}{T}} \frac{\left(e^{\frac{iT}{N_S}} - 1\right)^2 e^{iT}}{(e^{iT}-1)e^{\frac{iT}{N_S}}} - e^{\frac{iT}{N_S}}. \tag{4.27}$$

A closed form solution for the optimal number of order periods, N_S^*, cannot be determined in general from equation (4.27); therefore, for the analysis in Chapters 4-6, the optimal values of N_S^* and N_D^* to minimize the Total Cost are found by complete enumeration of all possible values (where $\frac{T}{N_S}$ and $\frac{T}{N_D}$ are integers).

4.2 Scenario analysis

Consider a baseline supply chain setting where the forecast period T is 180 days, the lean SCS total production cost, $K_L + M_L$, to deliver a single product to the customer is \$100, the average demand $\bar{d}$ is 275 units per day (approximately 100,000 units per year), demand forecast error f during the forecast period is constant, the ordering cost O_S and O_D are both \$200, and the lean index for the supply side and demand side are equal, $\gamma = \beta$. The values for supply side and demand side lead times and service levels for each SCS are taken from Table 3.3. Using this as a baseline supply chain setting, the Total Cost function for an agile SCS is

$$C_{AA1}(\tau, \delta, \psi, i) = e^{10i}\left[275\gamma K_L\left(\frac{180u_{180}}{N_S} + \frac{25.4603f}{\sqrt{N_S}}\right) + 200u_{180}\right] + e^{3i}\left[275\gamma(100 - K_L)\left(\frac{180v_{180}}{N_D} + \frac{25.4603f}{\sqrt{N_D}}\right) + 200v_{180}\right]. \quad (4.28)$$

The Total Cost function for a lean SCS is

$$C_{LL1}(\tau, \delta, \psi, i) = e^{81i}\left[275K_L\left(\frac{180u_{180}}{N_S} + \frac{40.8758f}{\sqrt{N_S}}\right) + 200u_{180}\right] + e^{21i}\left[275(100 - K_L)\left(\frac{180v_{180}}{N_D} + \frac{40.8758f}{\sqrt{N_D}}\right) + 200v_{180}\right]. \quad (4.29)$$

${N_S}^*$ and ${N_D}^*$ for each of the scenarios presented in Figure 3.4 are found by the complete enumeration of equations (4.28) and (4.29) for each SCS. The Total Cost of each SCS are compared $\left(C_{AA1}(\tau, \delta, \psi, i)\left({N_{S_A}}^*, {N_{D_A}}^*\right) \text{ and } C_{LL1}(\tau, \delta, \psi, i)\left({N_{S_L}}^*, {N_{D_L}}^*\right)\right)$ and the SCS with the lowest Total Cost is shown in Figure 4.1 for each of the scenarios described in Figure 3.4. (LL denotes a lean SCS with a lean strategy employed on both the demand and supply side of the supply chain and AA denotes an agile SCS with an agile strategy adopted on both the demand and supply side of the supply chain.)

				Demand Forecast Error: Low			Demand Forecast Error: Medium			Demand Forecast Error: High		
				Cost of Capital: Low	Med.	High	Cost of Capital: Low	Med.	High	Cost of Capital: Low	Med.	High
Lean Index	High	*RMP*	High	LL	LL	LL	LL	LL	LL	LL	LL	LL
			Med.	LL	LL	LL	LL	LL	LL	LL	LL	LL
			Low	LL	LL	LL	LL	LL	LL	LL	LL	LL
	Med.	*RMP*	High	LL	LL	LL	LL	LL	LL	LL	LL	LL
			Med.	LL	LL	AA	LL	LL	AA	LL	AA	AA
			Low	LL	LL	AA	LL	AA	AA	LL	AA	AA
	Low	*RMP*	High	LL	LL	AA	LL	AA	AA	AA	AA	AA
			Med.	LL	AA	AA	AA	AA	AA	AA	AA	AA
			Low	AA	AA	AA	AA	AA	AA	AA	AA	AA

Agile SCS (AA)

Lean SCS (LL)

Figure 4.1: SCS with the lowest Total Cost (Lean and Agile only)

Some general managerial insights can be learned from the examination of Figure 4.1 concerning the SCS that results in the lowest Total Cost, with respect to demand forecast error, cost of capital, lean index and *RMP*. With all other terms held constant, as demand forecast error decreases from high to low, the SCS that results in the lowest Total Cost may move from an agile SCS to a lean SCS. Figure 4.1 shows support for the Fisher Model when the objective is cost minimization, for supply chains where the lean index is not at a high level, that an agile SCS is the preferred SCS for products with high demand forecast error and a lean SCS is the preferred SCS for products with low demand forecast error.

As the cost of capital decreases, the SCS that results in the lowest Total Cost may move from an agile SCS to a lean SCS. In addition, for those supply chains where a large percentage of the production costs are incurred at the supplier (low *RMP*), an agile SCS is more likely to result in a lower Total Cost than a lean SCS. However, when a large percentage of the production costs are located closer to the customer (high *RMP*), a lean SCS is more likely to result in a lower Total Cost. Lastly, as the ratio of production cost for an agile SCS to a lean SCS increases, a lean SCS is more likely to result in a lower Total Cost than an agile SCS.

One of the key product characteristics Fisher (1997) used to distinguish a product as functional or innovative was demand forecast error, where the demand forecast error was less than 10% for a functional product and 40% or more for an innovative product. As discussed earlier, not all products are easily classified as functional or innovative. This leads to the question of when does an agile SCS result in a lower Total Cost than a lean SCS for a product with functional demand characteristics? From the discussion of Figure 4.1, as demand forecast error decreases from high to low, and without consideration of the other characteristics, the SCS which results in the lowest Total Cost may move from an agile SCS to a lean SCS. However, when considering the other three characteristics examined in this research (lean index, *RMP*, and cost of capital) in addition to a low level of demand forecast error, we find that a lean SCS does not always result in a lower Total Cost than an agile SCS (8 of 27 scenarios).

4.2.1 Low demand forecast error

H2: The Total Cost of an agile SCS can be less than that of a lean SCS when demand forecast error is low, and an agile SCS becomes more attractive as *RMP* decreases, lean index decreases, and cost of capital increases.

From Figure 4.1, for a supply chain with low *RMP*, low lean index, and high cost of capital, an agile SCS does result in a lower Total Cost than a lean SCS when the demand forecast error is low, like that associated with a functional product. To examine *H2* further, consider the scenario with low *RMP*, low lean index, high cost of capital, and low demand forecast error. Figure 4.2 presents the relative Total Cost difference of an agile SCS compared to a lean SCS when one of these four characteristics is varied and the other three characteristics are held constant. The relative Total Cost percent difference, $\phi_{LL,1}$, of an agile SCS to a lean SCS is

$$\phi_{LL,1} = \frac{C_{AA,1}(\tau,\delta,\psi,i)\left(N_{S_A}{}^*,N_{D_A}{}^*\right)-C_{LL,1}(\tau,\delta,\psi,i)\left(N_{S_L}{}^*,N_{D_L}{}^*\right)}{C_{LL,1}(\tau,\delta,\psi,i)\left(N_{S_L}{}^*,N_{D_L}{}^*\right)} * 100. \tag{4.30}$$

Therefore, when $\phi_{LL,1}$ is less than zero an agile SCS results in a lower Total Cost than a lean SCS, and when $\phi_{LL,1}$ is greater than zero a lean SCS results in a lower Total Cost than an agile SCS. The horizontal axis of the upper left graph in Figure 4.2 indicates the relative manufacturing cost, defined as the percentage of manufacturing costs to total production costs for a lean SCS (note: $RMP = \frac{M_L}{K_L}$),

$$RMC = \frac{RMP}{1+RMP} = \frac{M_L}{K_L+M_L}. \tag{4.31}$$

When the value of RMC is 10%, RMP is at a low level (0.111); when the value of RMC is 50%, RMP is at a medium level (1.0); and when the value of RMC is 90%, RMP is at a high level (9.0).

Figure 4.2: Value of $\phi_{LL,1}$ when one characteristic is varied and the other three are fixed with low *RMP*, low lean index, high cost of capital, and low demand forecast error.

Setting equations (4.28) and (4.29) equal to each other and with three of the four characteristics held constant, we can determine the value of the fourth characteristic such that the Total Cost of an agile SCS and a lean SCS are equal. The values for N_S^* and N_D^* for each of the supply chain strategies when $\phi_{LL,1}$ equals zero are determined by complete enumeration. Consider the upper left graph in Figure 4.2, with low demand forecast error, low lean index, and high cost of capital. In this case, for the *RMP* value of approximately 17.03 ($RMC \approx 94.5\%$), the Total Cost of an agile SCS and a lean SCS are equal. A *RMP* value of 17.03 is much larger than the *RMP* value identified as high in Table 3.4, where the high *RMP* =9. Therefore, for a supply chain with low demand forecast error, low lean index, high cost of capital, and the remaining supply chain parameters are those described in Table 3.3, the *RMP* characteristics of the supply chain needs to be very high (almost 95% of production costs at the manufacturer) before a lean SCS results in a lower Total Cost than an agile SCS.

The demand forecast error value in Figure 4.2 where $\phi_{LL,1}$ equals zero (upper right graph) is -28.07%. As defined, the expected demand forecast error cannot be less than zero; therefore, with low *RMP*, low lean index, high cost of capital, and the remaining supply chain parameters described in Table 3.3, an agile SCS always results in a lower Total Cost than a lean SCS.

When the lean index value in Figure 4.2 is 1.029 (lower left graph), a value between the medium and high levels as described in Table 3.4, the Total Cost of an agile SCS is equal to that of a lean SCS. The cost of capital value in Figure 4.2 (lower right graph) where $\phi_{LL,1}$, equals zero is 4.62% annually, which is less than the cost of capital value defined as a low level in Figure 3.4, with low *RMP*, low demand forecast error, low lean index and the remaining supply chain parameters described in Table 3.3.

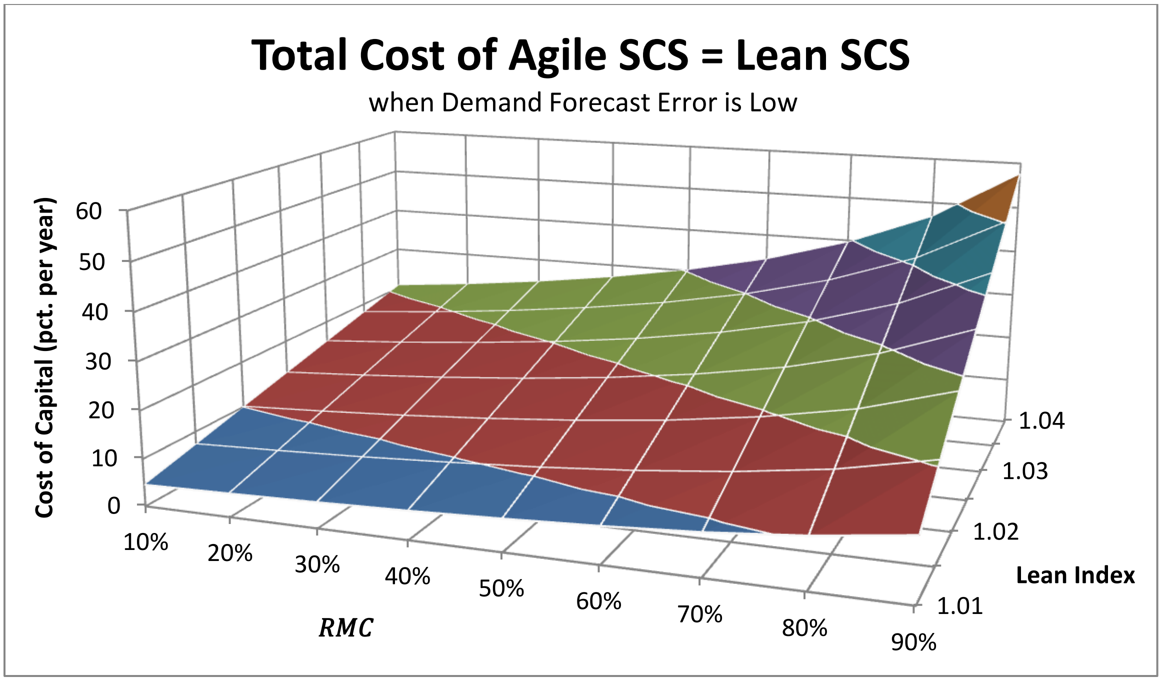


Figure 4.3: Cost of capital that makes $\phi_{LL,1} = 0$ as a function of the value of RMC (RMP) and the lean index value when demand forecast error is low as described in Table 3.4.

Figure 4.3 shows the annual percent cost of capital where the Total Cost of an agile SCS equals a lean SCS with respect to the RMC and the lean index value for a supply chain when the demand forecast error is low (10%). To interpret this surface graph, for a point above the surface an agile SCS will result in a lower Total Cost, and for a point below the surface a lean SCS results in a lower Total Cost (with low demand forecast error). Figure 4.3 demonstrates that the choice between an agile SCS and a lean SCS is more sensitive to RMC (and *RMP*) as the lean index increases and less sensitive to RMC as the cost of capital increases.

4.2.2 High demand forecast error

The previous section examined the situations where an agile SCS results in a lower Total Cost compared to a lean SCS for a product with functional demand characteristics. We now consider the question, when does a lean SCS result in a Total Cost less than an agile SCS for a product with innovative demand characteristics? From the discussion of Figure 4.1, as demand forecast error increases from low to high, and without consideration of the other characteristics, the SCS which results in the lowest Total Cost may move from a lean SCS to an agile SCS. However, when a supply chain considers the other three characteristics examined in this research in addition to a high level of demand forecast error we find that an agile SCS does not always result in a lower Total Cost than a lean SCS.

H3: The Total Cost of a lean SCS can be less than that of an agile SCS when demand forecast error is high, and a lean SCS becomes more attractive as *RMP* increases, lean index increases, and cost of capital decreases.

To examine *H3* further, consider the scenario with high *RMP*, medium lean index, low cost of capital, and high demand forecast error. Figure 4.4 presents the relative Total Cost difference of an agile SCS compared to a lean SCS when one of these four characteristics is varied and the other three characteristics are held constant.

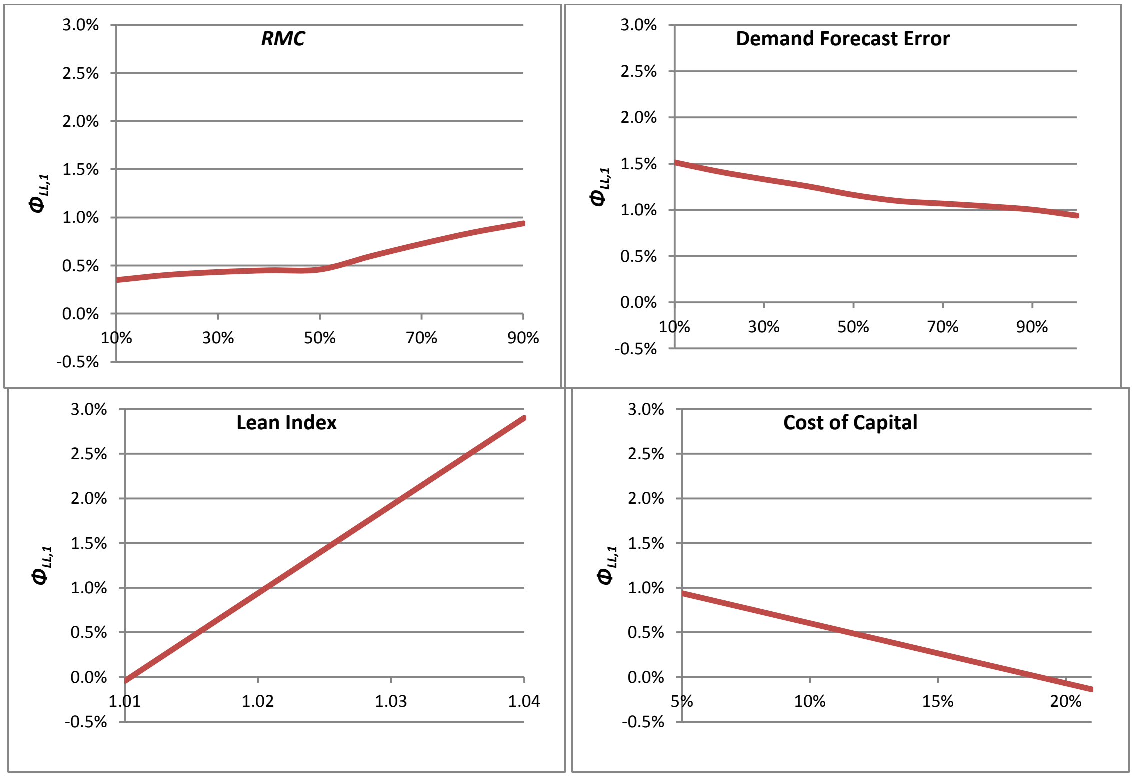


Figure 4.4: Value of $\phi_{LL,1}$ when one characteristic is varied and the other three are fixed with *RMP* high, lean index medium, cost of capital low, and demand forecast error high.

As with *H2*, the value of a characteristic where $\phi_{LL,1}$ equals zero is determined by setting equations (4.28) and (4.29) equal to each other, with three of the four characteristics held constant, and solving for the fourth characteristic. The values for N_S^* and N_D^* for each of the supply chain strategies are determined by complete enumeration. The *RMP* value where $\phi_{LL,1}$ equals zero in Figure 4.4 (upper left graph) is -0.0015. The value of *RMP* is bounded on the lower end at zero (when zero production costs are incurred at the manufacturer and 100% of the production costs are at the supplier): therefore, with high demand forecast error, low cost of capital, and medium lean index, a lean SCS results in a lower Total Cost than an agile SCS independent of the *RMP* value.

The demand forecast error value where $\phi_{LL,1}$ equals zero in Figure 4.4 (upper right graph) is 249%, a level of demand forecast error far greater than the high level of

100% described in Table 3.4. Hence, only for those supply chains where the demand uncertainty level is extremely high would an agile SCS produce a lower Total Cost than a lean SCS in this scenario. When the lean index value is 1.0104 in Figure 4.4 (lower left graph), just above the lean index low level described in Table 3.4, the Total Cost of an agile SCS and a lean SCS are equal. The cost of capital value where $\phi_{LL,1}$ equals zero in Figure 4.4 is 18.95% annually, a value larger than the cost of capital high level defined in Table 3.4.

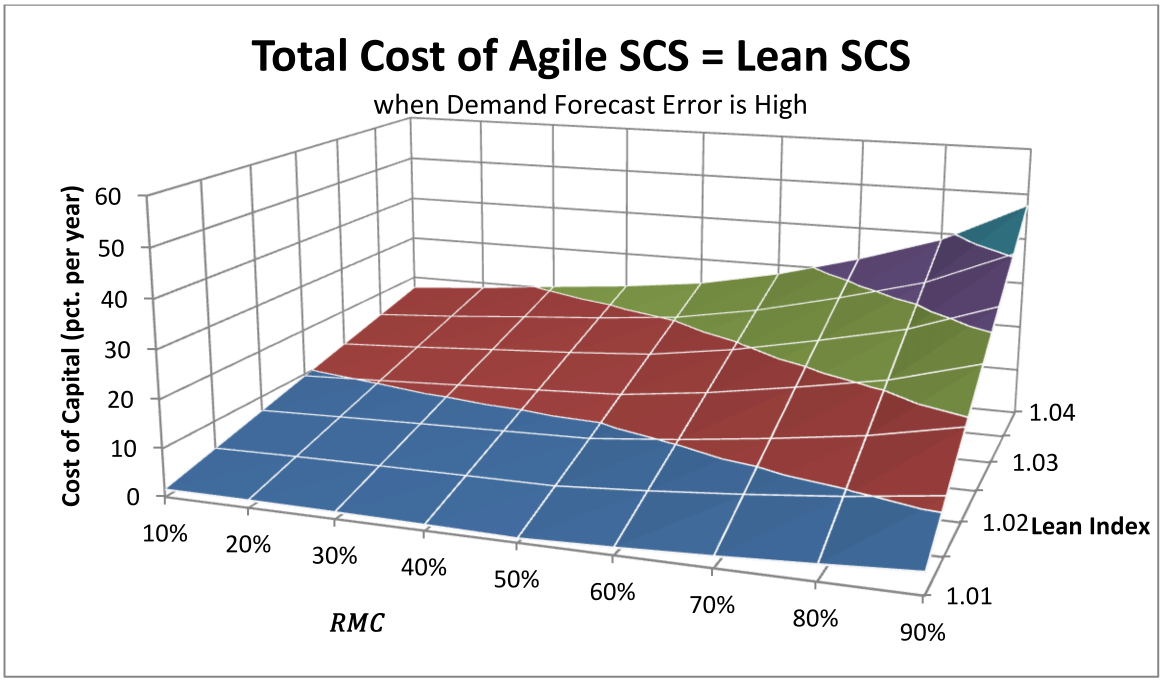


Figure 4.5: Cost of capital that makes $\phi_{LL,1} = 0$ as a function of the value of RMC (RMP) and the lean index value when demand forecast error is high as described in Table 3.4.

The surface in Figure 4.5 illustrates the parameter values for lean index, cost of capital, and RMC where the Total Cost of an agile SCS equals a lean SCS when demand forecast error is high. This surface is interpreted similarly to that of Figure 4.4; for points above the surface, an agile SCS results in a lower Total Cost, and for points below the surface a lean SCS results in a lower Total Cost. Figure 4.4 illustrates that the choice between an agile SCS and a lean SCS is more sensitive to lean index as RMC increases and is less sensitive to lean index as the cost of capital increases.

4.3 Sensitivity analysis

This section provides a sensitivity analysis of the baseline supply chain setting from section 4.2 to examine the impact of total production cost relative to ordering cost, expected demand, lead time, and service level on the relative cost difference between a lean SCS and an agile SCS. The purpose of the sensitivity analysis is to provide insight into how a change in the value of a single aspect of the supply chain (demand, product cost, or supply chain aspect) impacts the supply chain's propensity towards either a lean or an agile SCS, when only one of the four characteristics is varied (*RMP*, lean index, cost of capital, and demand forecast error) and the other three characteristics are held constant at their medium level, as defined in Table 3.4.

The multiple lines in each of Figures 4.6-4.21 illustrate the value of $\phi_{LL,1}$ as one aspect of the supply chain is varied for several different levels of one characteristic, with the other three characteristics held at their medium level and other parameters at the baseline supply chain setting as presented in section 4.2. When $\phi_{LL,1}$ is greater than zero a lean SCS results in a lower Total Cost and when $\phi_{LL,1}$ is less than zero an agile SCS should be employed to minimize Total Cost.

4.3.1 Total production cost to total order processing cost

The Total Cost function considers two major categories of costs: (i) production costs for supply side purchasing and demand side manufacturing, where the values of these costs are dependent upon the SCS, and (ii) total order processing cost for the demand side and supply side, which are assumed to be independent of the SCS. Therefore, as the ratio of total production cost to total order processing cost increases for a supply chain, the likelihood increases that a lean SCS will result in a lower Total Cost than an agile SCS.

H4: As the ratio of total production cost to total order processing cost increases, the supply chain's propensity towards a lean SCS increases.

In the baseline supply chain setting presented in section 4.2, the total production cost per unit is $K_L + M_L = \$100$ and the total order processing cost per order is $O_S + O_D = \$400$. Therefore, the baseline ratio of total production cost to total order processing cost is 0.25. The values for total production cost and total order processing cost that define the x-axis of Figures 4.6-4.9 are given in Table 4.1.

Ratio of total production cost to total order processing cost	0.0025	0.0125	0.0250	0.1250	0.2500
Total Production Cost	$1	$5	$10	$50	$100
Total order processing cost	$400	$400	$400	$400	$400

Table 4.1: Legend for the x-axis of Figures 4.6-4.9; showing the ratio of total production cost to total order processing cost.

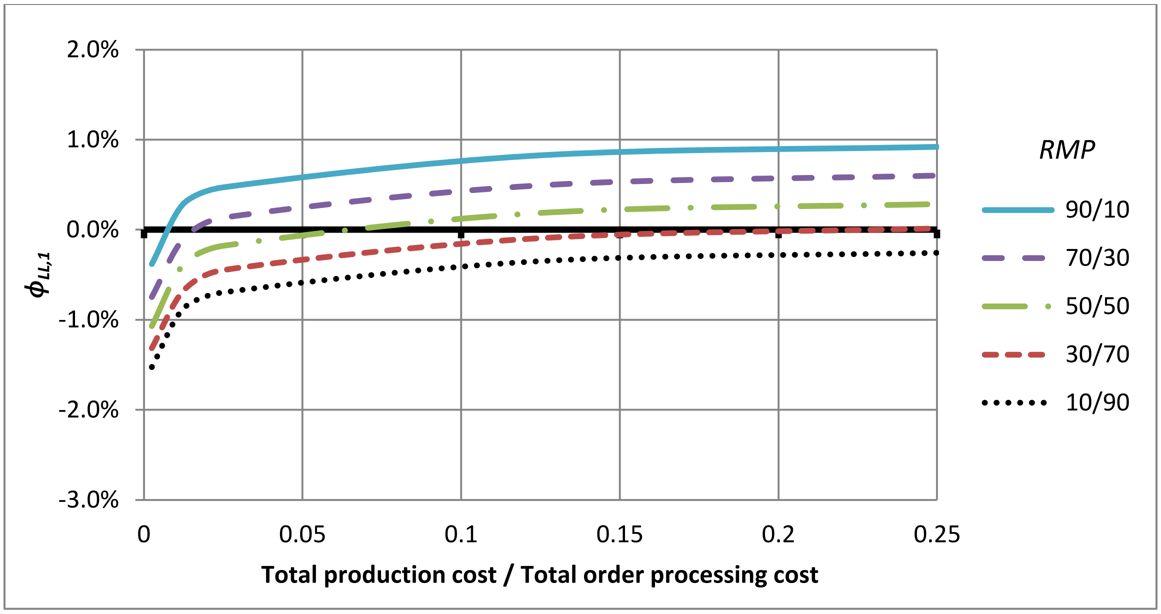


Figure 4.6: Value of $\phi_{LL,1}$ with respect to the ratio of total production cost to total order processing cost for different *RMP* levels.

From Figure 4.6, when the supply chain structure is such that when the majority of the total production costs are incurred at the manufacturer (i.e. *RMP* is large), the total order processing cost must be much larger than the total production cost for an agile SCS to result in a lower Total Cost than a lean SCS. In turn, when the vast majority (90%+) of the total production costs of a product are incurred at the supplier (i.e. $RMP < 10/90$) and the lean index, cost of capital and the demand forecast error at a medium level per Table 3.4, an agile SCS results in a lower Total Cost than a lean SCS and this is independent of the value of the ratio of total production cost to total order processing cost. However, for all other supply chain strategies a significant change in supply chain structure or in the ratio of total production cost to total order processing cost can impact the SCS that results in the lowest Total Cost .

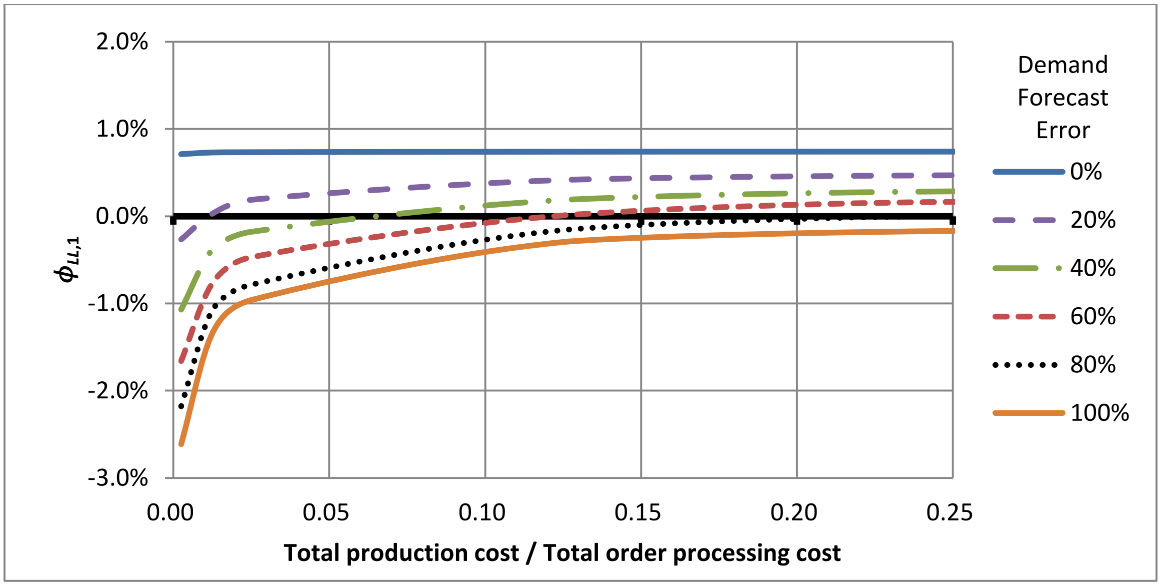


Figure 4.7: Value of $\phi_{LL,1}$ with respect to the ratio of total production cost to total order processing cost for different demand forecast error levels.

Figure 4.7 illustrates the impact to $\phi_{SCS,1}$ when the ratio of total production cost to total order processing cost and demand forecast error vary with all other terms held constant. When the demand forecast error is stable, the SCS that results in the lowest Total Cost is relatively insensitive to the ratio of total production cost to total order processing cost when the ratio is greater than 0.025 or the total order processing cost is not more than 40 times the total production cost. When the demand forecast error is unstable, the SCS is relatively insensitive to the ratio of production cost to order processing cost, when the ratio is greater than 0.10 or the total order processing cost is not more than 10 times the total production cost. Also, when the ratio of total production cost to total order processing cost is greater than approximately 2.0 (not shown in Figure 4.7) a lean SCS results in a lower Total Cost than an agile SCS independent of the level of demand forecast error, with all other terms constant.

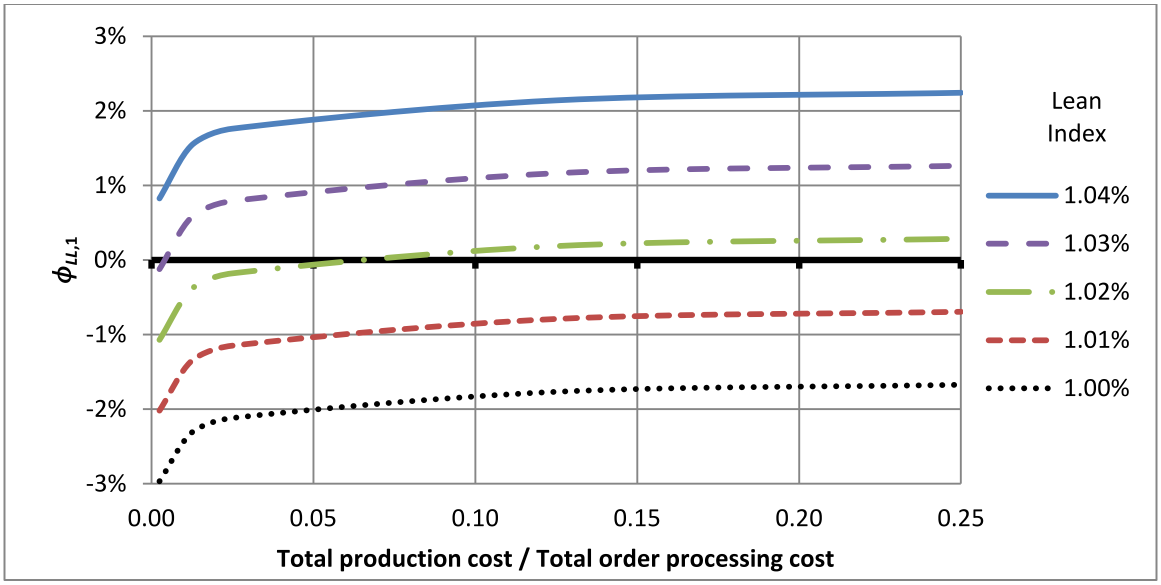


Figure 4.8: Value of $\phi_{LL,1}$ with respect to the ratio of total production cost to total order processing cost for different lean index levels.

Figure 4.8 shows that when the lean index is high a lean SCS results in the lower Total Cost, and when the lean index is low an agile SCS results in the lower Total Cost, independent of the values considered for the ratio of total production cost to total order processing cost, when all other parameters are constant.

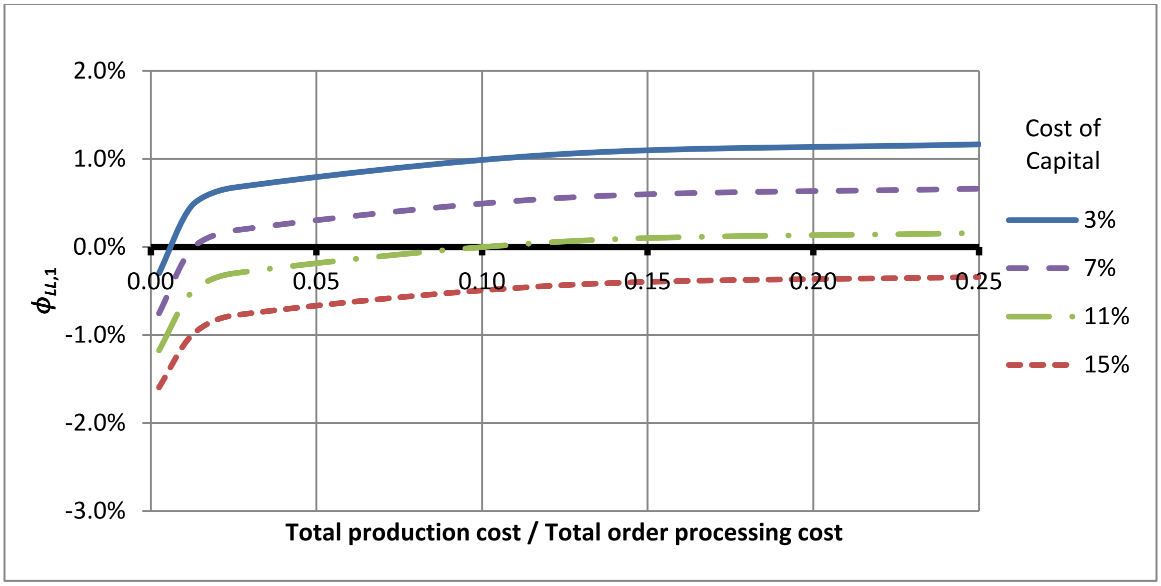


Figure 4.9: Value of $\phi_{LL,1}$ with respect to the ratio of total production cost to total order processing cost for different cost of capital levels.

From Figure 4.9, when the cost of capital is high, an agile SCS results in a lower Total Cost than a lean SCS independent of the values for the ratio of total production cost to total order processing cost considered. In addition, when the total order processing cost is much larger than the total production cost of a single unit, a supply chain should employ an agile SCS to minimize Total Cost.

Figures 4.6-4.9 demonstrates support for *H4*, when the ratio of total production cost to total order processing cost increases, the supply chain's propensity will move towards a lean SCS, since all curves are increasing. Therefore, when a supply chain implements an improvement that reduces the total order processing cost (i.e. an online order placement system or setup cost reduction), relative to the total production cost, the value of $\phi_{LL,1}$ will increase and the supply chain's SCS preference will move towards a lean SCS. In contrast, when a supply chain implements a cost reduction action that reduces the total production cost relative to the total order processing cost of a product the supply chain's propensity will move towards an agile SCS.

4.3.2 Average daily demand

The second aspect of the supply chain to be examined in the sensitivity analysis is the impact of the value of expected demand on the relative cost difference between the Total Cost of an agile SCS and a lean SCS. When all other parameters are constant, an increase in expected daily demand will increase the total production cost side of the model without impacting the total order processing cost, because total order processing cost is modeled independent of expected demand. To offset this rise in the total production cost a supply chain could increase the number of orders placed during the forecast period, thereby delaying when some of the production costs are incurred. However, the model in this dissertation does not allow a supply chain to place more than one order per day. Once the expected demand value reaches a level where orders are placed daily, any additional increase in expected demand has little to no impact on the relative cost difference between an agile SCS and a lean SCS.

H5: As the expected daily demand rate increases, the supply chain's propensity towards a lean SCS increases.

The expected daily demand rate in the baseline supply chain setting presented in this dissertation is 275 units or 99,000 units annually. The values of expected daily demand rate and annual demands for 360 days per year considered in Figures 4.10-4.13 are given in Table 4.2.

Expected daily demand rate	10	50	100	500	1,000
Expected annual demand	3,600	18,000	36,000	180,000	360,000

Table 4.2: Legend for the x-axis of Figures 4.10-4.14 with expected daily demand and annual demand.

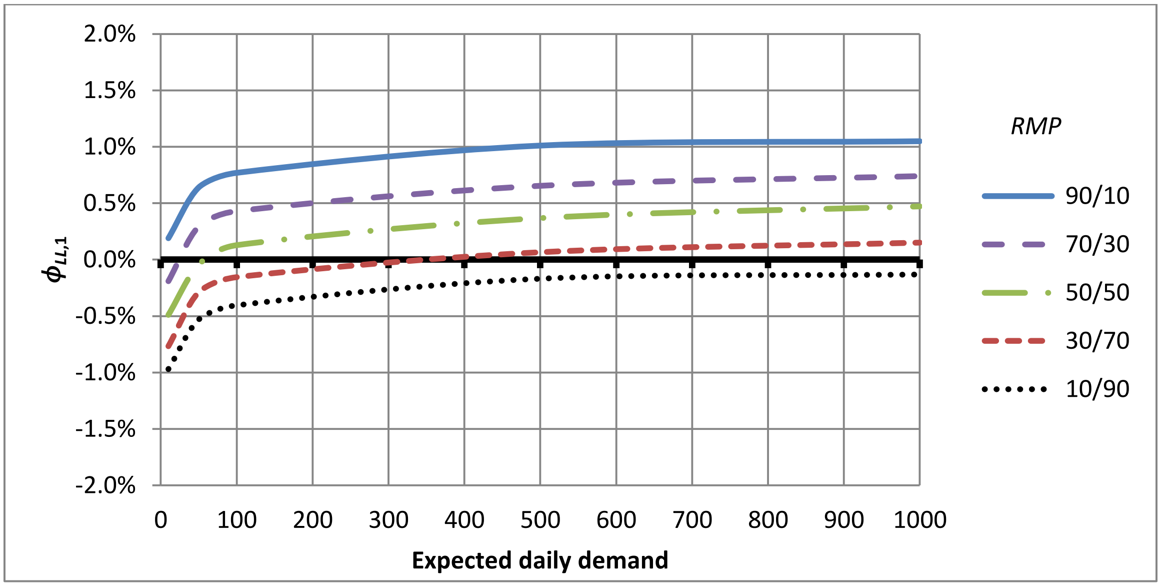


Figure 4.10: Value of $\phi_{LL,1}$ with respect to the expected daily demand rate for different *RMP* levels.

From Figure 4.10, for a given value of *RMP* when the expected daily demand rate is changed significantly there was only a small impact to the value of $\phi_{LL,1}$, except for small expected daily demand rates (<50). For supply chain structures where the vast majority (≥90%) of total production costs are incurred at the supplier, an agile SCS results in a slightly lower Total Cost than a lean SCS for all the values of expected daily demand rate considered in this analysis. In addition, for supply chain structures where the vast majority (≥90%) of total production costs are incurred at the manufacturer, a lean SCS results in a slightly lower Total Cost (at worst about 1%) than an agile SCS for all the values of expected daily demand rate considered in this analysis.

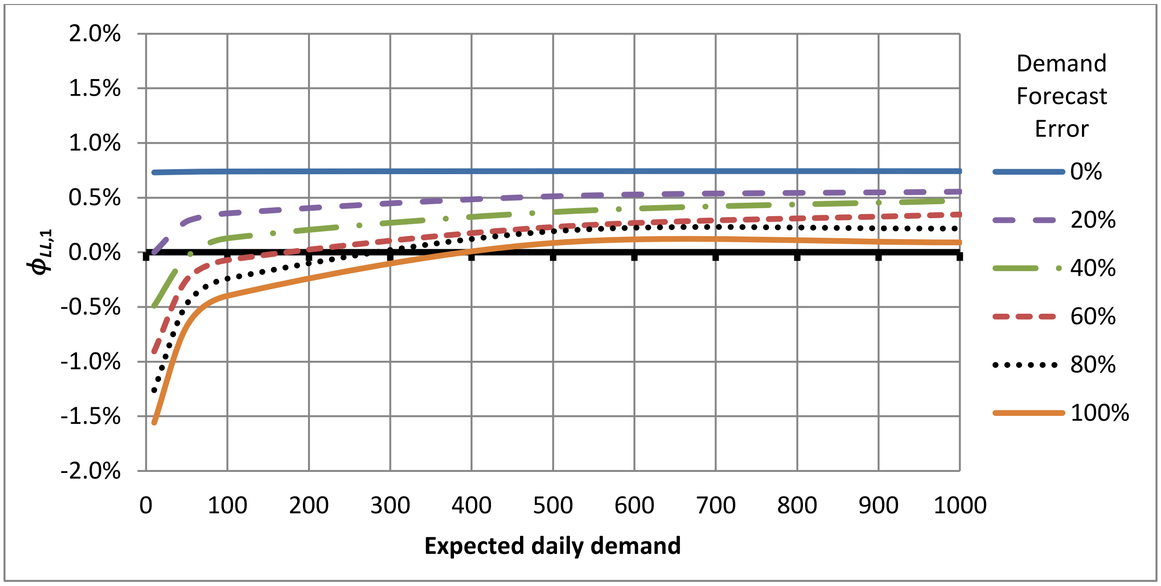


Figure 4.11: Value of $\phi_{LL,1}$ with respect to the expected daily demand rate for different demand forecast error levels.

Figure 4.11 shows that the sensitivity of relative Total Cost to a change in the expected daily demand rate is greatest, although small, when demand forecast error is greater than 20% and expected daily demand is less than 400 units. For expected daily demand rates greater than 400 units a lean SCS results in a slightly lower Total Cost than an agile SCS (<1%) and the relative Total Cost difference is not sensitive to an increase in the expected daily demand rate. When the demand forecast error is less than 20% a lean SCS results in a slightly lower Total Cost than an agile SCS independent of the expected daily demand rate, when all others terms are constant.

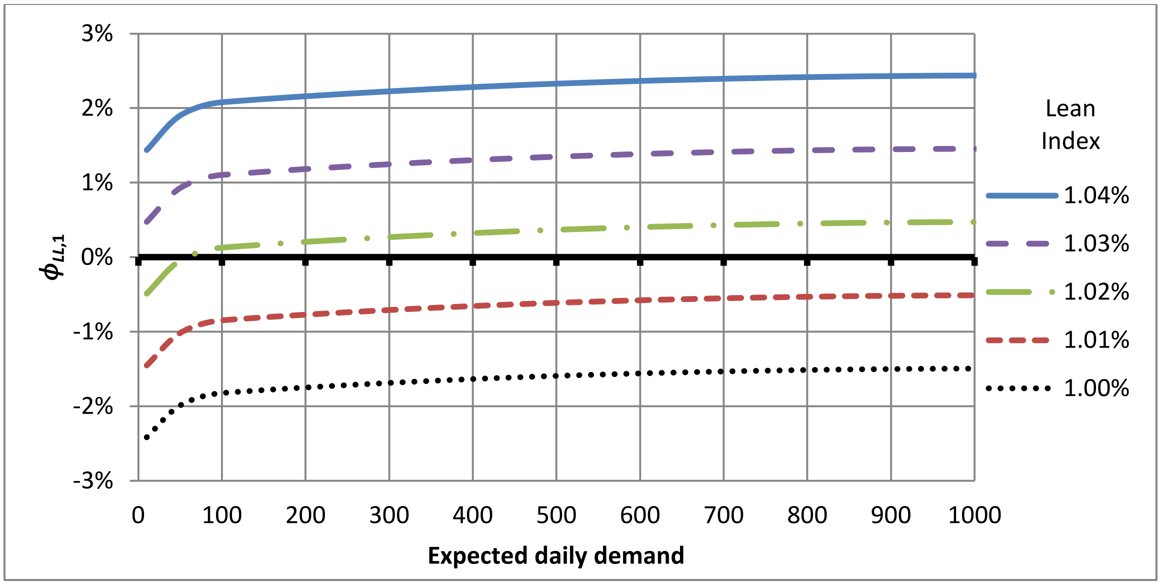


Figure 4.12: Value of $\phi_{LL,1}$ with respect to the expected daily demand rate for different lean index levels.

Similar to Figure 4.8, in Figure 4.12 a small change in the lean index results in a relatively large change in the value of $\phi_{LL,1}$. For values of expected daily demand rates greater than 100 units, an increase in expected daily demand rate has a very small impact on the relative Total Cost percent difference, for a given lean index value.

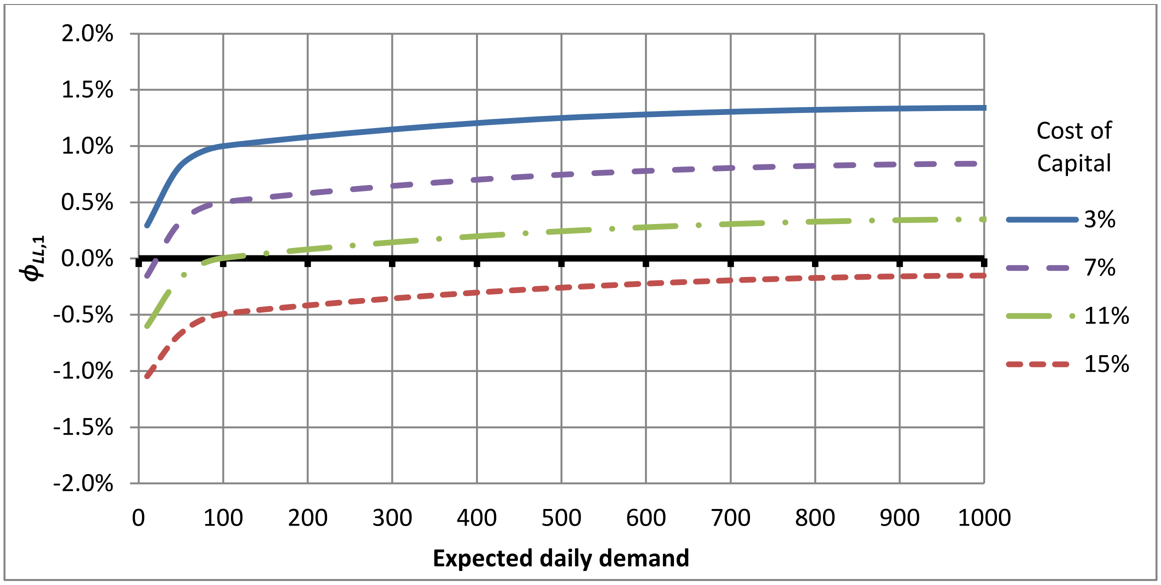


Figure 4.13: Value of $\phi_{LL,1}$ with respect to the expected demand rate for different cost of capital levels.

Figure 4.13 shows that for expected daily demand rate values greater than 100 and when the cost of capital is less than 11%, a lean SCS results in the lowest Total Cost when compared to an agile SCS. When the cost of capital is high an agile SCS results in a slightly lower Total Cost than a lean SCS independent of the expected daily demand rates considered here.

Figure 4.10-4.13 demonstrates support for *H5* when expected daily demand rate increases the supply chain's propensity moves towards a lean SCS, since all curves are increasing. Therefore, as the value of expected daily demand rate increases the likelihood that a lean SCS will minimize Total Cost relative to an agile SCS increases. However, the relative Total Cost difference between the supply chain strategies is constrained by the frequency at which orders could be placed (at most once per day).

4.3.3 Supply side lead time

The next aspect of the supply chain examined in this section is the ratio of supply side lead times between the supply chain strategies. The baseline supply chain setting models the lean SCS with a long supply side lead time, $L_{L,S} = 60$ days, such as for an off-shore supplier. The agile SCS assumes a shorter supply side lead time, $L_{A,S} = 7$ days, such as for a domestic supplier. Obviously firms employing a lean SCS are not only located off-shore (with long lead times); but might be located domestically with a shorter lead time or in a location where the lead time is longer than that considered in the baseline supply chain setting. Supply chain responsiveness is the primary objective of an agile SCS and a secondary objective of a lean SCS. Longer lead times increase the inventory costs of a supply chain and increase the risk associated with obsolescence and spoilage. An increase in the ratio $\frac{L_{L,S}}{L_{A,S}}$ indicates the supply side lead time of the lean SCS lengthens relative to the supply side lead time of the agile SCS, resulting in an increase in the inventory costs of the lean SCS relative to the agile SCS. Therefore, lengthening the lean SCS supply chain relative to the supply chain length of the agile SCS will result in a decrease in the relative Total Cost percent difference between the supply chain strategies.

H6: When the ratio $\frac{L_{L,S}}{L_{A,S}}$ increases, the supply chain's propensity towards an agile SCS increases.

For the baseline supply chain setting the supply lead time ratio (for a lean SCS to an agile SCS) is 60/7 = 8.57. The values for the lean SCS supply side lead time and the agile SCS supply side lead times used to develop the x-axis values for $\frac{L_{L,S}}{L_{A,S}}$ in Figures 4.14-4.17, are given in Table 4.3.

$L_{L,S}/L_{A,S}$	1	2	4	8	12	16
$L_{L,S}$	7	14	28	56	84	112
$L_{A,S}$	7	7	7	7	7	7

Table 4.3: Legend for the x-axis of Figure 23-26, ratio of the lean SCS supply side lead time to the agile supply side lead time.

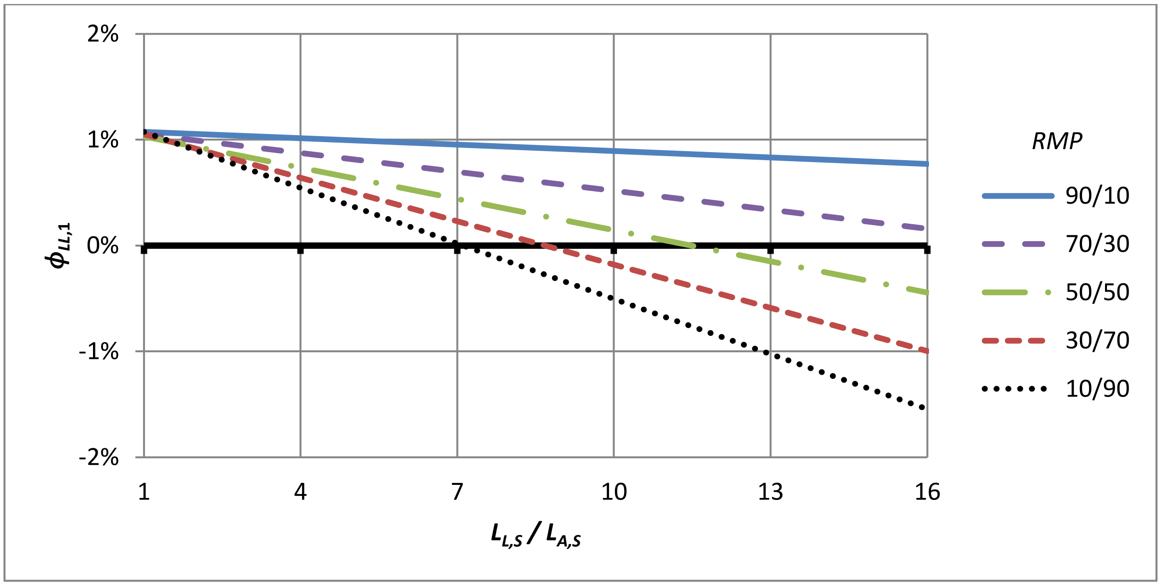


Figure 4.14: Value of $\phi_{LL,1}$ with respect to the ratio $\frac{L_{L,S}}{L_{A,S}}$ for different *RMP* levels.

From Figure 4.14, when the supply chain structure is such that the majority of the total production costs are incurred at the manufacturer (high *RMP*), the value of $\phi_{LL,1}$ is insensitive to changes in the supply side lead time ratio and a lean SCS results in a slightly lower Total Cost than an agile SCS for the supply side lead time ratios considered. As the supply chain structure moves from a *RMP* value of 90/10 to 10/90, the sensitivity of $\phi_{LL,1}$ to the supply side lead time ratio increases. When the lean SCS supply side lead time equals the agile SCS supply side lead time, the value of $\phi_{LL,1}$ is about 1% for all values of *RMP* considered. However, Figure 4.14 supports hypothesis *H6* that as the ratio of the supply side lead time for a lean SCS to that of an agile SCS increases the propensity of a supply chain is to move towards an agile SCS.

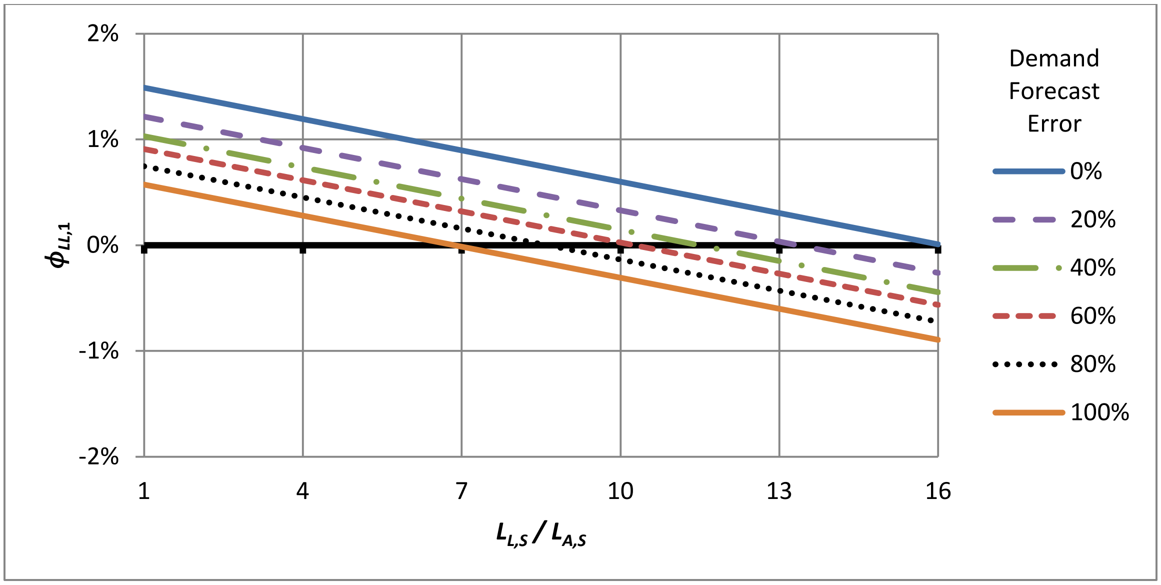


Figure 4.15: Value of $\phi_{LL,1}$ with respect to the ratio $\frac{L_{L,S}}{L_{A,S}}$ for different demand forecast error levels.

Figure 4.15 indicates even when the demand forecast error is 0%, the value of $\phi_{LL,1}$ decreases as the supply side lead time ratio increases. Therefore, an agile SCS results in a lower Total Cost than a lean SCS when the ratio between the supply side lead time of a lean SCS and an agile SCS is greater than 16 and the demand forecast error is 0%, when all other parameters are constant. When the demand forecast error is 100% the supply side lead time ratio where $\phi_{LL,1}$ is equal to zero is approximately 7. Figure 4.15 supports hypothesis *H6* that as the ratio of lean SCS supply side lead time to the agile SCS supply side lead time increases, the propensity of the supply chain moves towards an agile SCS.

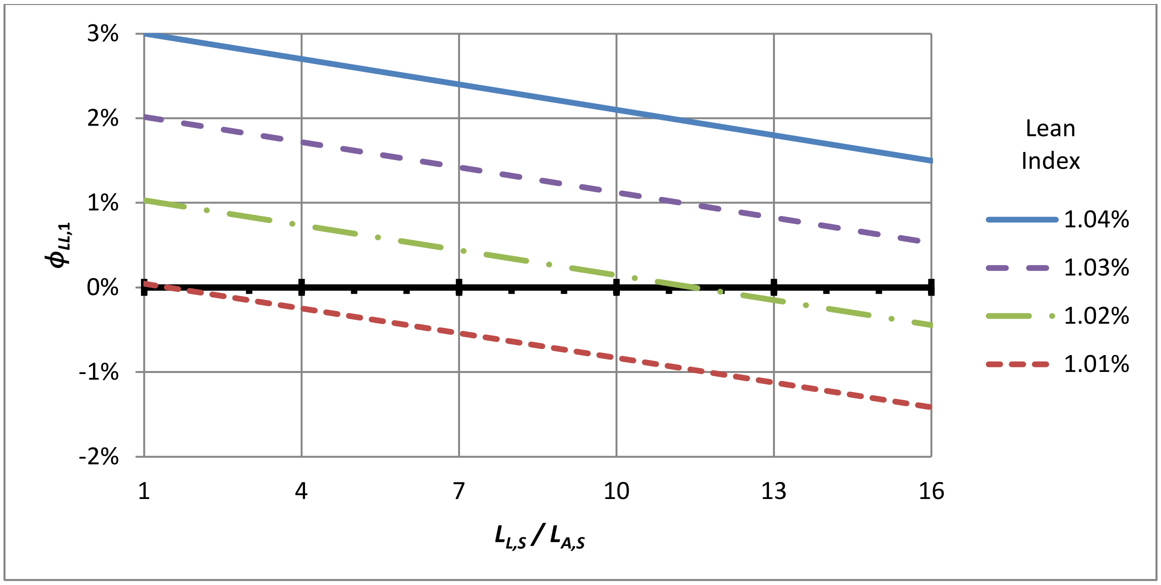


Figure 4.16: Value of $\phi_{LL,1}$ with respect to the ratio $\frac{L_{L,S}}{L_{A,S}}$ for different lean index values.

When the lean index is low, the value of $\phi_{LL,1}$ is less than zero for all values of the supply side lead time ratio greater than approximately 1.5. As the lean index increases the value of the supply side lead time ratio where $\phi_{LL,1}$ equals zero increases. When the lean index is increased to a medium level (1.02%), the value of the supply side lead time ratio where $\phi_{SCS,1}$ equals zero increases to almost 12. Figure 4.16 supports hypothesis *H6* that as the ratio $\frac{L_{L,S}}{L_{A,S}}$ increases, the propensity of the supply chain is to move towards an agile SCS.

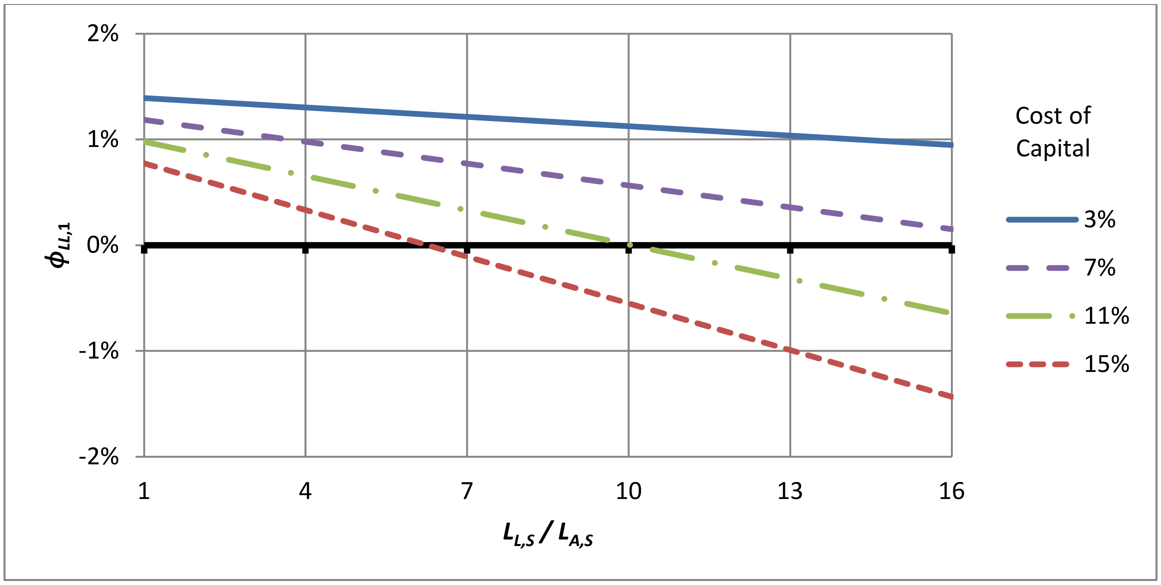


Figure 4.17: Value of $\phi_{LL,1}$ with respect to the ratio $\frac{L_{L,S}}{L_{A,S}}$ for different cost of capital levels.

Figure 4.17 shows when the cost of capital is 3%, and therefore the cost of holding inventory is low, the value of $\phi_{LL,1}$ is insensitive to changes in the supply side lead time ratio. The sensitivity of $\phi_{LL,1}$ to a change in the value of $\frac{L_{L,S}}{L_{A,S}}$, increases as the cost of capital increases. In addition, when the supply side lead time ratio is less than 5, then a lean SCS results in a lower Total Cost than an agile SCS. For the range of cost of capital values considered, when the cost of capital is greater than 7% and the supply side lead time ratio was greater than 6 the value of $\phi_{LL,1}$ may be less than zero, dependent on the value of the determinants. Figure 4.17 also supports hypothesis *H6*.

Although there are values for the characteristics considered in the dissertation where $\phi_{LL,1}$ is rather insensitive to changes in the supply side lead time ratio, such as when *RMP* is high or when the cost of capital is low, generally the value of $\phi_{LL,1}$ decreases as the supply side lead time ratio increases. Figures 4.14-4.17 all show support for hypothesis *H6*: that as the ratio $\frac{L_{L,S}}{L_{A,S}}$ increases, the propensity of the supply chain is to move towards an agile SCS. Therefore, with all other parameters held constant and either a reduction in the agile SCS supplier's lead time or a deterioration (increase) in the lean SCS supplier's lead time, the propensity of the supply chain moves towards an agile SCS.

4.3.4 Agile SCS service level

The last aspect of the supply chain examined in this section is the agile SCS service level. The agile SCS Total Cost model assumes a 90% service level and the lean SCS Total Cost model assumes a 98% service level. With all other parameters being equal, the lower service level of the agile SCS results in a lower safety stock inventory level and a lower inventory holding cost. Therefore, as the difference between the service levels of an agile SCS and a lean SCS narrows the cost advantage from the agile SCS lower service level will decrease. In addition, the agile SCS lead time is assumed shorter than the lean SCS lead time for both the demand and supply side of the supply chain. In practice there can be supply chains where the agile SCS is expected to have a service level higher than 90% and the supply chain may require the service level of an agile SCS to equal that of the lean SCS.

H7: When the service level of the agile SCS increases, the supply chain's propensity towards a lean SCS increases.

The analysis considers the impact the value of the agile SCS service level has on the relative Total Cost percent difference between an agile SCS and a lean SCS. The analysis starts from a scenario where an agile SCS results in a lower Total Cost than a lean SCS: medium *RMP*, medium lean index, high demand forecast error, and high cost of capital; the value for the level of each characteristic is given in Table 3.4.

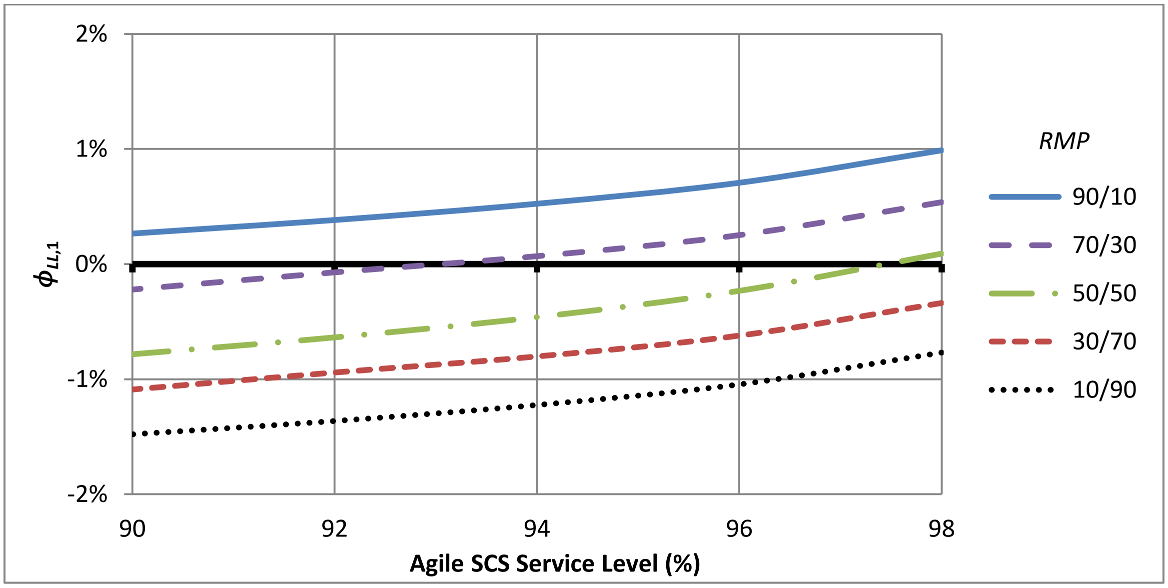


Figure 4.18: Value of $\phi_{LL,1}$ with respect to the agile SCS service level for different *RMP* levels.

From Figure 4.18, when the supply chain structure is such that the large majority (>90%) of the total production costs are incurred at the manufacturer or at the supplier the SCS that results in the lowest Total Cost is independent of changes in the agile SCS service level, assuming all other parameters are constant. Figure 4.18 supports hypothesis *H7* that as the agile SCS service level increases the propensity of a supply chain is to move towards a lean SCS.

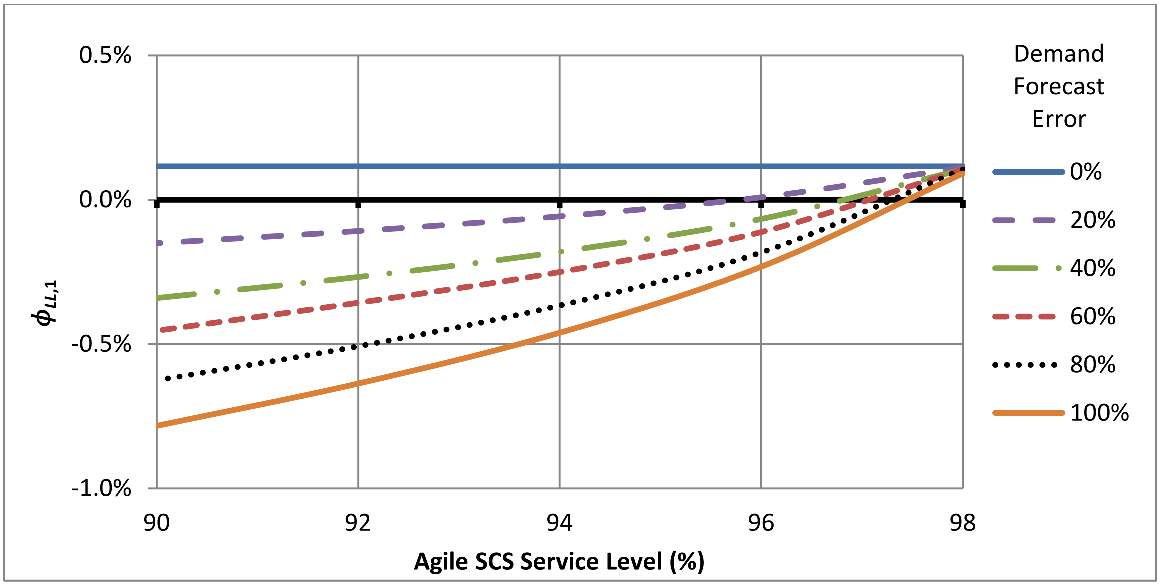


Figure 4.19: Value of $\phi_{LL,1}$ with respect to the agile SCS service level for different demand forecast error levels.

Figure 4.19 indicates when the demand forecast error is 0%, the value of $\phi_{LL,1}$ is insensitive to the changes in the agile SCS service level, and a lean SCS results in a slightly lower Total Cost than an agile SCS for the characteristics considered. The sensitivity of $\phi_{LL,1}$ to changes in the agile SCS service level increases as the value of demand forecast error increases. When demand forecast error is 100% an agile SCS results in a slightly lower Total Cost until the agile SCS service level value increases to nearly 98%. Figure 4.19 supports hypothesis *H7* that as the agile SCS service level increases the propensity of the supply chain moves towards a lean SCS.

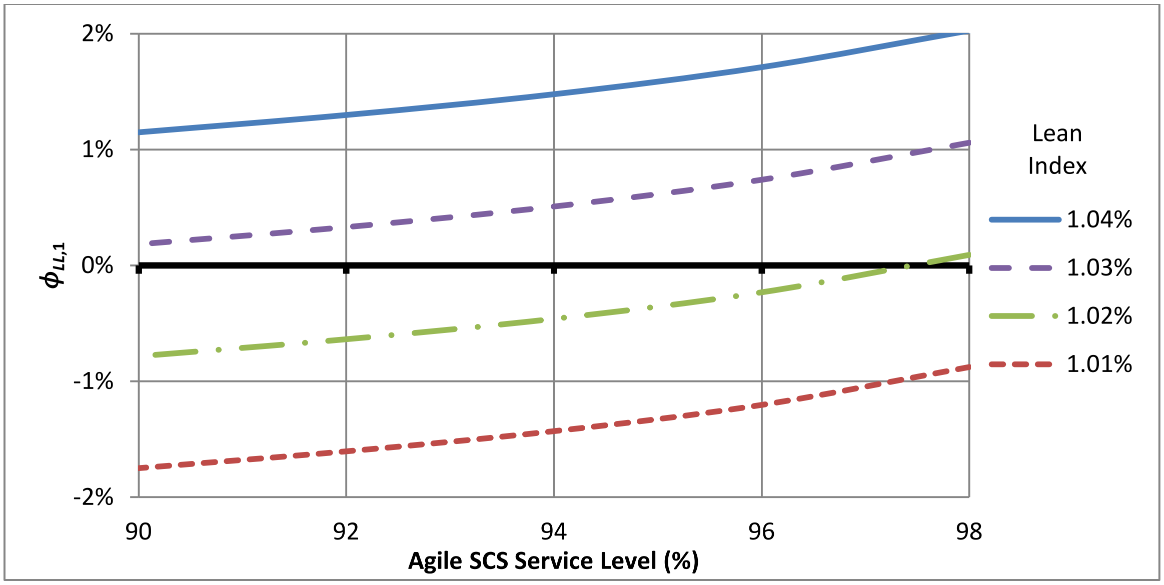


Figure 4.20: Value of $\phi_{LL,1}$ with respect to the agile SCS service level for different lean index levels.

When the lean index level is high (1.04) or when the lean index level is low (1.01), the SCS that results in the lowest Total Cost is independent of the agile SCS service level from 90% to 98% for the characteristics considered. Figure 4.20 supports hypothesis *H7* that as the agile SCS service level increases, the propensity of the supply chain is to move towards a lean SCS.

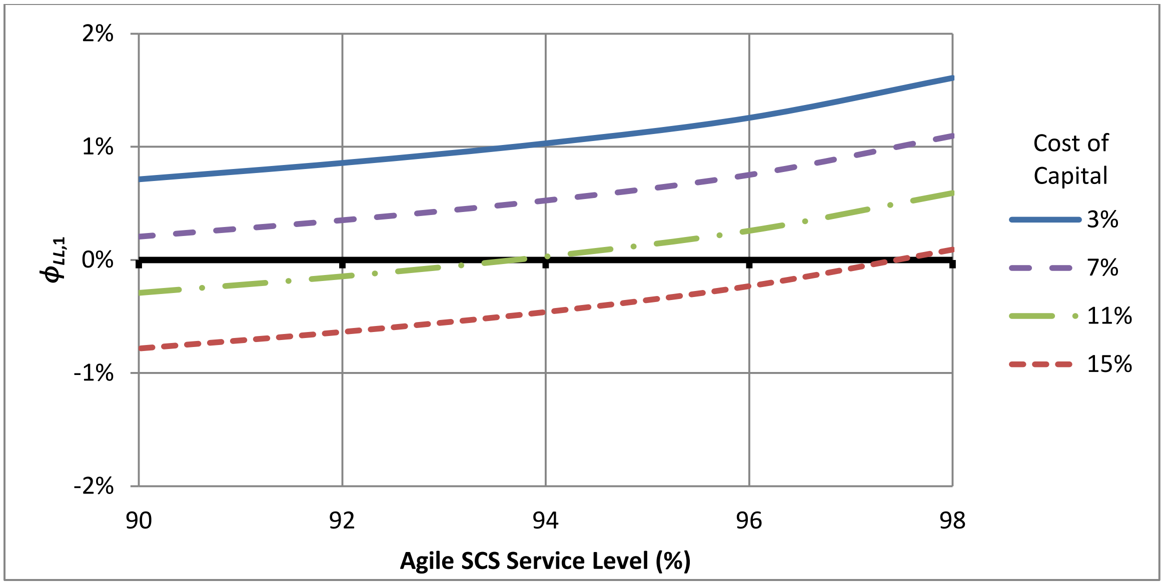


Figure 4.21: Value of $\phi_{LL,1}$ with respect to the agile SCS service level for different cost of capital levels.

Figure 4.21 shows for the scenarios considered, when the cost of capital is less than 9%, slightly less than medium level described in Table 3.4, or when the agile SCS service level is greater than 97%, a lean SCS results in a lower Total Cost than an agile SCS. When the cost of capital is 15.8%, which is greater than the cost of capital high level described in Table 3.4, and the service levels of an agile SCS and a lean SCS are both 98% the Total Cost of an agile SCS and a lean SCS are equal. Therefore, for values of cost of capital greater than 15.8% an agile SCS results in a lower Total Cost than a lean SCS when the agile SCS service level is 98% or less, for the scenarios considered. The graph in Figure 4.21 also supports hypothesis *H7*.

Although there are values for the characteristics considered in the dissertation where $\phi_{LL,1}$ is rather insensitive to changes in the agile SCS service level, such as with high *RMP* (90/10) or high lean index (1.04%), in general the value of $\phi_{LL,1}$ increases as the agile SCS service level increases when all other parameters are held constant. Figures

4.18-4.21 all support hypothesis *H7*: that as the agile SCS service level increases, the propensity of the supply chain is to move towards a lean SCS.

4.4 Summary

The primary purpose of this chapter was to identify the scenarios such that a "mismatch" of SCS and product type resulted in a lower Total Cost than a "match" of SCS and product type, when considering a lean SCS and an agile SCS only. The secondary purpose was to examine the sensitivity of the relative Total Cost difference between an agile SCS and a lean SCS when one aspect at a time of the supply chain was changed.

To address the primary purpose of the chapter, two hypotheses, *H2* and *H3*, were evaluated and support was found for both hypotheses. Hypothesis *H2* proposed that an agile SCS could result in a lower Total Cost than a lean SCS when a product has demand characteristics of a functional product (i.e. low demand uncertainty). This research demonstrated that for a functional product an agile SCS can result in a lower Total Cost than a lean SCS, independent of the demand forecast error value, which would be described as a "mismatch" of SCS and product type.

Hypothesis *H3* proposes that a lean SCS can result in a lower Total Cost than an agile SCS when the product has demand characteristic of an innovative product (i.e. high demand uncertainty). This research demonstrated that a lean SCS can result in a lower Total Cost than an agile SCS as long as the level of demand forecast error was less than 249%. Therefore, this demonstrated a scenario such that a "mismatch" of SCS and product type would result in a lower Total Cost than for a “match” of SCS and product type.

Figure 4.22 expands Figure 3.4 to show the SCS that results in the lowest Total Cost for each of the eighty-one scenarios for the four characteristics. A “Mismatch” occurs when an agile SCS is best with low demand forecast error, and when a lean SCS is best with high demand forecast error. From Figure 4.22, we see when demand forecast error is low, in eight of the twenty-seven scenarios an agile SCS results in a lower Total Cost than a lean SCS. When demand forecast error is high, for fourteen of the twenty-seven scenarios a lean SCS results in a lower Total Cost than an agile SCS.

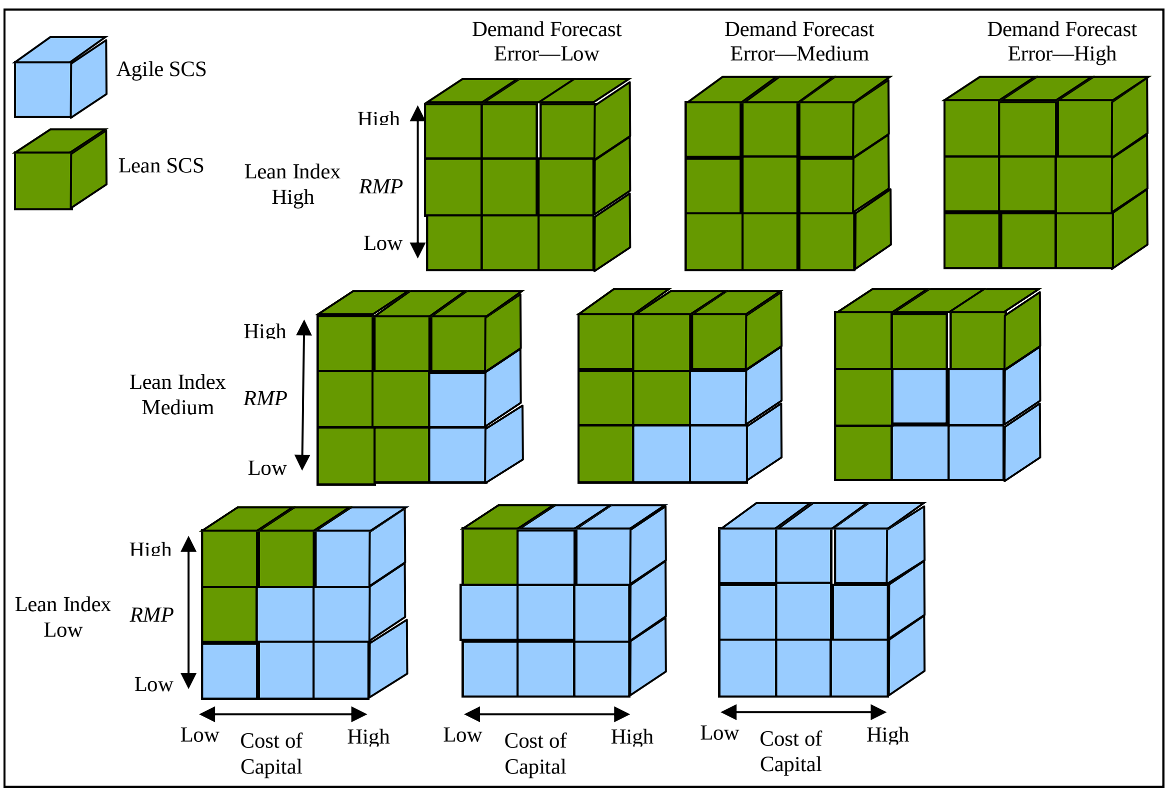


Figure 4.22: The SCS which results in the lowest Total Cost for all scenarios considered.

For the second purpose of this chapter, the aspects of the supply chain considered were the ratio of total production cost to total order processing cost, the expected daily demand rate, the ratio of the supply side lead time for a lean SCS to that of an agile SCS, and the agile SCS service level. A change in the relative total production and total order processing cost impacts the relative Total Cost difference between the two supply chain strategies. The analysis supports hypothesis *H4* that when the total production cost is reduced relative to total order processing cost, the supply chain's preference of SCS moves towards an agile SCS, when all other parameters are constant. In addition, when the total order processing cost is reduced relative to the total production cost, the relative Total Cost difference increases; meaning the supply chain propensity moves towards a lean SCS, when all other parameters are held constant. Therefore, as a supply chain acts to reduce the Total Cost of the supply chain, focusing on either production costs or ordering costs alone, a change in SCS may be required to minimize the Total Cost.

Next this chapter examines the impact that a change in expected daily demand has on the Total Cost difference, when expected demand is constant for the forecast period. The analysis supports hypothesis *H5* that as the value of expected daily demand increases, the propensity of the minimum cost supply chain is to move towards a lean SCS.

The next aspect this chapter examines is the influence of the ratio of the lean SCS supply side lead time to the agile SCS supply side lead time, $\frac{L_{L,S}}{L_{A,S}}$. The analysis supports hypothesis *H6* that an increase in the ratio $\frac{L_{L,S}}{L_{A,S}}$ results in an increase in the supply chain's propensity towards an agile SCS. The analysis found that an improvement in the agile SCS supply side lead time or a degradation (increase) in the lean SCS supply side lead time results in a negative change in the Total Cost percent difference between the two supply chain strategies, when all other parameters are constant.

The last aspect this chapter examines is the impact the agile SCS service level has on the relative Total Cost difference between an agile SCS and a lean SCS. The analysis supports hypothesis *H7* that when the service level of the agile SCS increases, the supply chain's propensity moves towards a lean SCS. When the service levels of the supply chain strategies are equal, a lean SCS is more likely to result in a lower Total Cost than an agile SCS when compared to the baseline supply chain setting where the service level values differed between the supply chain strategies. However, even when service level of the supply chain strategies are equal, there are scenarios where an agile SCS results in a lower Total Cost than a lean SCS, such as when the supply chain *RMP* value is low, the lean index is low, and cost of capital is high, as described in Table 3.4, for the scenario considered.

5. Supply chain strategy selection

Question Q2 is addressed by this chapter: Under what combination of supply chain characteristics does each SCS minimize total supply chain cost?

To examine this question, this dissertation considers four possible supply chain strategies: lean SCS, leagile SCS, agilean SCS, and agile SCS. In addition to examining the SCS that results in the lowest Total Cost for each of the eighty-one scenarios presented in Figure 3.4, this chapter considers the impact on which SCS results in the lowest Total Cost in the setting where expected demand is a linear function of time and demand forecast error is constant for the forecast period.

5.1 Problem description

This chapter considers the case where expected demand is a linearly increasing or decreasing function of time and expected demand forecast error is constant for the forecast period $[0, T]$. It is assumed that the demand rate at time zero is $d(0) > 0$ and the demand rate at the end of the forecast period is $d(T) \geq 0$. The parameter α is the slope of the linear demand function, given by

$$\alpha = \frac{d(T) - d(0)}{T} \tag{5.1}$$

The expression for expected demand at time t is

$$d(t) = \alpha t + d(0). \tag{5.2}$$

The continuous expected demand function is discretized as d_j for day j for $j = 0, 1, 2, \ldots, T$ where $d(0) = d_0$ as follows

$$d_j = \int_{j-1}^{j} d(t)\,dt = \frac{\alpha}{2}(2j-1) + d_0. \qquad \forall\, j = 1,2,\dots,T \ (5.3)$$

Realized demand $\hat{d}_j$ is assumed to be normally distributed about expected demand d_j during the forecast period; $N[d_j, \sigma_j{}^2]$, with expected demand forecast error constant for the forecast period,

$$f_j = f. \qquad \forall\, j = 1,2,\dots,T \ (5.4)$$

Expected demand, realized demand and the demand forecast error are assumed constant for each j day and the expected daily demands are assumed mutually independent. The standard deviation of realized demand about expected demand is defined by substituting equations (5.3) and (5.4) into equation (3.14),

$$\sigma_j = \frac{f * d_j}{0.6745}. \qquad \forall\, j = 1,2,\dots,T \ (5.4)$$

The standard deviation of the cumulative distribution function (CDF) of demand for each order period is the square root of the summation of the expected demand variances for the entire order period. The CDF for the demand side of the supply chain is (from question 3.16):

$$\sigma_{n_D} = \sqrt{\sum_{j=j_{(n_D-1)}+1}^{j_{n_D}} \sigma_j{}^2}$$

$$= \frac{f}{0.6745}\sqrt{\sum_{j=j_{(n_D-1)}+1}^{j_{n_D}} d_j{}^2}. \qquad \forall\, n_D = 1,2,\dots,N_D (5.5)$$

The CDF for the supply side of the supply chain is determined similarly as

$$\sigma_{n_S} = \sqrt{\sum_{j=j_{(n_S-1)}+1}^{j_{n_S}} \sigma_j{}^2}$$

$$= \frac{f}{0.6745} \sqrt{\sum_{j=j_{(n_S-1)}+1}^{j_{n_S}} {d_j}^2}. \quad \forall\, n_S = 1, 2, \ldots, N_S \quad (5.6)$$

The safety stock inventory level for each order period, n_D and n_S, independent of the SCS is (similar to equation 3.17 and 3.18)

$$Z_{X,Y}\sigma_{n_Y}. \quad (5.7)$$

The model assumes that initial safety stock inventory level for the demand side and supply side of the supply chain are zero, given by (similar to equation 3.19)

$$Z_{X,D}\sigma_0 = 0 \quad (5.8)$$

and

$$Z_{X,S}\sigma_0 = 0. \quad (5.9)$$

The change in safety stock inventory level from the previous order period to the next order period for the demand side and the supply side are determined by equations (3.20) and (3.21), respectively.

The Total Cost function when expected demand is a linear function of time and demand forecast error is constant, $C_2(\tau, \delta, \psi, i)$, is determined by substituting equations (5.3), (5.5), and (5.6) into equation (3.26),

$$C_2(\tau, \delta, \psi, i) =$$

$$e^{i(L_{XS}+L_{XD})} \left[\sum_{n_S=1}^{N_S} \left(K_X \left\{\left(\sum_{j=j_{n_S-1}+1}^{j_{n_S}} d_j\right) + Z_{X,S}\left(\sigma_{n_S} - \sigma_{(n_S-1)}\right)\right\} + O_S\right) e^{-i\left(j_{n_S-1}\right)}\right] +$$

$$e^{i(L_{XD})} \left[\sum_{n_D=1}^{N_D} \left(M_X \left\{\left(\sum_{j=j_{n_D-1}+1}^{j_{n_D}} d_j\right) + Z_{X,D}\left(\sigma_{n_D} - \sigma_{(n_D-1)}\right)\right\} + O_D\right) e^{-i\left(j_{n_D-1}\right)}\right]. \quad (5.10)$$

The attributes $\tau, \psi,$ and i are the same as defined in the general Total Cost function $C(\tau, \delta, \psi, i)$, equation (3.26). The parameters included in the demand attribute group, δ, are: expected demand, d_j, as determined from the expected demand at time 0 d_0, and the rate of change in expected demand α; standard deviation of the CDF, σ_{n_D} and σ_{n_S}, as determined from the demand forecast error f_j and the standard deviation of demand σ_j; and the length of the forecast period T. Thus $\delta = \left[d_j, d_0, \alpha, \sigma_{n_D}, \sigma_{n_S}, f_j, \sigma_j, T\right]$.

The general expression $\sum_{j=j_{n_Y-1}+1}^{j_{n_Y}} d_j$ from equation (5.10), independent of the supply chain side, is transformed to the total expected demand during the order period n_Y as follows

$$\sum_{j=j_{n_Y-1}+1}^{j_{n_Y}} d_j = \sum_{j=j_{n_Y-1}+1}^{j_{n_Y}} \alpha j + \sum_{j=j_{n_Y-1}+1}^{j_{n_Y}} \left(d_o - \frac{\alpha}{2}\right) = \frac{\alpha}{2}\left(\frac{n_Y T}{N_Y} - \left(\frac{(n_Y-1)T}{N_Y} + 1\right) + 1\right)\left(\frac{n_Y T}{N_Y} + \left(\frac{(n_Y-1)T}{N_Y} + 1\right)\right) + \left(d_o - \frac{\alpha}{2}\right)\left(\frac{n_Y T}{N_Y} - \left(\frac{(n_Y-1)T}{N_Y} + 1\right) + 1\right) =$$

$$\frac{\alpha T^2}{2{N_Y}^2}(2n_Y - 1) + \frac{d_0 T}{N_Y}. \tag{5.11}$$

As in chapter 4, the total demand side and supply side order processing cost for the forecast period $[0, T]$ is a special case of a geometric series where the partial sum is given by equation (4.12) and expressed by

$$O_D \sum_{n_D=1}^{N_D} e^{-i\left(j_{(n_D-1)}\right)} = O_D \frac{\left(1-e^{-iT}\right)}{\left(1-e^{\frac{-iT}{N_D}}\right)} = O_D v_T \tag{5.12}$$

and

$$O_S \sum_{n_S=1}^{N_S} e^{-i\left(j_{(n_S-1)}\right)} = O_S \frac{(1-e^{-iT})}{\left(1-e^{\frac{-iT}{N_S}}\right)} = O_S u_T. \tag{5.13}$$

Equation (5.10) is restated following the substitution of equations (5.11), (5.12), and (5.13) as

$$C_2(\tau, \delta, \psi, i) =$$

$$e^{i(L_S+L_D)}\left[K_X \sum_{n_S=1}^{N_S}\left(\frac{\alpha T^2(2n_S-1)+2d_0 N_S T}{2{N_S}^2} + Z_{XS}\left(\sigma_{n_S} - \sigma_{(n_S-1)}\right)\right)e^{-i\left(j_{(n_S-1)}\right)} + O_S u_T\right]$$

$$+e^{i(L_D)}\left[M_X \sum_{n_D=1}^{N_D}\left(\frac{\alpha T^2(2n_D-1)+2d_0 N_D T}{2{N_D}^2} + Z_{XD}\left(\sigma_{n_D} - \sigma_{(n_D-1)}\right)\right)e^{-i\left(j_{(n_D-1)}\right)} + O_D v_T\right]$$

(5.14)

5.2 Scenario analysis

The baseline supply chain setting considered in Chapter 4 is also used for Chapter 5: the forecast period T is 180 days, the lean SCS total production cost $K_L + M_L$ to deliver a single product to the customer is \$100, the initial expected demand d_0 is 275 units, demand forecast error f during the forecast period is constant, the ordering cost O_S and O_D are both \$200, and the lean index for the supply side and demand side are equal, $\gamma = \beta$. The values for supply side and demand side lead times and service levels for each SCS are taken from Table 3.3. Using this baseline supply chain setting, the Total Cost function for an agile SCS when expected demand is a linear function of time and demand forecast error is constant for the forecast period is given by

$$C_{AA,2}(\tau, \delta, \psi, i) =$$

$$e^{10i}\left[\gamma K_L \sum_{n_S=1}^{N_S}\left(\frac{\alpha 180^2(2n_S-1)+99{,}000N_S}{2{N_S}^2} + 1.280\left(\sigma_{n_S} - \sigma_{(n_S-1)}\right)\right)e^{-i\left(\frac{(n_S-1)180}{N_S}\right)} + 200u_{180}\right] +$$

$$e^{3i}\left[\gamma M_L \sum_{n_D=1}^{N_D}\left(\frac{\alpha 180^2(2n_D-1)+99{,}000N_D}{2{N_D}^2} + 1.280\left(\sigma_{n_D} - \sigma_{(n_D-1)}\right)\right)e^{-i\left(\frac{(n_D-1)180}{N_D}\right)} + 200v_{180}\right]. \quad (5.15)$$

The Total Cost function for an agilean SCS when expected demand is a linear function of time and demand forecast error is constant for the forecast period is given by

$$C_{AL,2}(\tau, \delta, \psi, i) =$$

$$e^{28i}\left[\gamma K_L \sum_{n_S=1}^{N_S}\left(\frac{\alpha 180^2(2n_S-1)+99{,}000N_S}{2{N_S}^2} + 1.280\left(\sigma_{n_S} - \sigma_{(n_S-1)}\right)\right)e^{-i\left(\frac{(n_S-1)180}{N_S}\right)} + 200u_{180}\right] +$$

$$e^{21i}\left[M_L \sum_{n_D=1}^{N_D}\left(\frac{\alpha n_D 180^2(2n_D-1)+99{,}000N_D}{2{N_D}^2} + 2.055\left(\sigma_{n_D} - \sigma_{(n_D-1)}\right)\right)e^{-i\left(\frac{(n_D-1)180}{N_D}\right)} + 200v_{180}\right]. \quad (5.16)$$

The Total Cost function for a leagile SCS when expected demand is a linear function of time and demand forecast error is constant for the forecast period is given by

$$C_{LA,2}(\tau, \delta, \psi, i) =$$

$$e^{63i}\left[K_L \sum_{n_S=1}^{N_S}\left(\frac{\alpha 180^2(2n_S-1)+99{,}000N_S}{2{N_S}^2} + 2.055\left(\sigma_{n_S} - \sigma_{(n_S-1)}\right)\right)e^{-i\left(\frac{(n_S-1)180}{N_S}\right)} + 200u_{180}\right] +$$

$$e^{3i}\left[\gamma M_L \sum_{n_D=1}^{N_D}\left(\frac{\alpha n_D 180^2(2n_D-1)+99{,}000N_D}{2{N_D}^2} + 1.280\left(\sigma_{n_D} - \sigma_{(n_D-1)}\right)\right)e^{-i\left(\frac{(n_D-1)180}{N_D}\right)} + 200v_{180}\right]. \quad (5.17)$$

The Total Cost function for a lean SCS when expected demand is a linear function of time and demand forecast error is constant for the forecast period is given by

$$C_{LL,2}(\tau, \delta, \psi, i) =$$

$$e^{81i}\left[K_L \sum_{n_S=1}^{N_S}\left(\frac{\alpha 180^2(2n_S-1)+99{,}000N_S}{2N_S{}^2} + 2.055\left(\sigma_{n_S} - \sigma_{(n_S-1)}\right)\right)e^{-i\left(\frac{(n_S-1)180}{N_S}\right)} + 200u_{180}\right] +$$

$$e^{21i}\left[M_L \sum_{n_D=1}^{N_D}\left(\frac{\alpha n_D 180^2(2n_D-1)+99{,}000N_D}{2N_D{}^2} + 2.055\left(\sigma_{n_D} - \sigma_{(n_D-1)}\right)\right)e^{-i\left(\frac{(n_D-1)180}{N_D}\right)} + 200v_{180}\right]. \quad (5.18)$$

${N_S}^*$ and ${N_D}^*$ for each of the scenarios presented in Figure 3.4 are found by the complete enumeration of equations (5.15), (5.16), (5.17), and (5.18) for each SCS. The optimal number of order periods with respect to the SCS are used to determine the Total Cost values for $C_{AA,2}(\tau, \delta, \psi, i)\left({N_{S_A}}^*, {N_{D_A}}^*\right)$, $C_{AL,2}(\tau, \delta, \psi, i)\left({N_{S_A}}^*, {N_{D_L}}^*\right)$, $C_{LA,2}(\tau, \delta, \psi, i)\left({N_{S_L}}^*, {N_{D_A}}^*\right)$, and $C_{LL,2}(\tau, \delta, \psi, i)\left({N_{S_L}}^*, {N_{D_L}}^*\right)$ when expected demand is a linear function of time and demand forecast error is constant. The Total Costs for each SCS are compared and the SCS with the lowest Total Cost for each of the eighty-one scenarios defined by Figure 3.4 is presented in Figure 5.1.

		Demand Forecast Error: Low			Demand Forecast Error: Medium			Demand Forecast Error: High		
		Cost of Capital			Cost of Capital			Cost of Capital		
Lean Index	*RMP*	Low	Med.	High	Low	Med.	High	Low	Med.	High
High	High	LL	LL	LL	LL	LL	LL	LL	LL	LL
High	Med.	LL	LL	LL	LL	LL	LL	LL	LL	LL
High	Low	LL	LA	LA	LL	LA	LA	LL	LA	LA
Med.	High	LL	LL	AL	LL	AL	AL	AL	AL	AL
Med.	Med.	LL	LL	AL	LL	LL	AL	LL	AL	AA
Med.	Low	LA	LA	AA	LA	LA	AA	LA	AA	AA
Low	High	AL	AL	AL	AL	AL	AA	AL	AA	AA
Low	Med.	LL	AA	AA	AL	AA	AA	AA	AA	AA
Low	Low	LA	AA	AA	AA	AA	AA	AA	AA	AA

Lean SCS (LL) | Agile SCS (AA) | Leagile SCS (LA) | Agilean SCS (AL)

Figure 5.1: The SCS with the lowest Total Cost (expected demand and demand forecast error constant)

From examination of Figure 5.1 some general managerial insights can be identified. First, a leagile SCS should be considered only when the supply structure is such that the majority of the production costs are incurred at the supplier (low *RMP*). Second, a leagile SCS is the appropriate SCS to minimize Total Cost when the supply chain structure is such that *RMP* is low, the lean index is high and the cost of capital is medium or high, independent of the level of demand forecast error. Third, an agilean SCS should be considered when the supply chain structure is such that the majority of the production costs are incurred at the manufacturer (high *RMP*) and the lean index is either low or medium. Finally, a supply chain with the following characteristics is very sensitive to changes in demand forecast error, since it is the only scenario considered where the SCS that results in the lowest Total Cost changes at each level of demand forecast error considered: low lean index, medium *RMP*, and the low cost of capital. This supply chain scenario and others where the appropriate SCS is dependent on the demand forecast error are examined in greater detail in section 5.3.2.

5.3 Sensitivity analysis

The sensitivity analysis in this chapter focuses on the two aspects of the supply chain that may be the most uncertain: expected demand and demand forecast error. The other characteristics examined in this dissertation are likely known with greater certainty than those associated with expected demand.

The lean index, the ratio of total production cost for an agile SCS to a lean SCS, will not likely change drastically over a six month period. In those cases where material pricing could be subject to drastic changes in cost, such as from large changes in raw material costs or exchange rates, it is assumed that the supply chain will employ the appropriate financial risk-hedging techniques to mitigate the supply chain’s risk. *RMP* is the characteristic considered in this dissertation that the supply chain (or at least the focal firm of the supply chain) has the greatest control over during the forecast period. Any changes to the supply chain structure, including *RMP*, would likely be known several months, or more, in advance of implementation. Although many aspects of the cost of capital are outside the control of supply chain members, this research assumes that any changes in the cost of capital will generally be gradual with respect to time, as could result when the economies of the nations where supply chain members are located are relatively stable.

The purposes of these sensitively analyses are to examine the impacts of (i) the magnitude of changes in expected demand, and (ii) the anticipated level of demand forecast error on the SCS that minimized the Total Cost. The analyses are presented in two steps. The first step considers various values for α to identify those scenarios where the SCS that results in the lowest Total Cost for the forecast period is dependent on the value of α. The second step examines scenarios where the SCS that results in the lowest Total Cost for a specific combination of lean index, *RMP*, and cost of capital is dependent upon the level of demand forecast error.

5.3.1 Expected demand changes over time

Several values for α are considered to expand the analysis presented in section 5.2. The purpose of the section is to examine the impact a forecasted increase or decrease in expected demand over the forecast period has on the SCS that results in the lowest Total Cost. Each of the eighty-one scenarios presented in Figure 3.4 are evaluated with α equal to the following seven values: -1.53, -0.76, 0, 0.76, 1.53, 6.11, and 13.75. Table 5.1 presents the level of expected demand at the end of the 180 day forecast period and the percent change in expected demand over the period for the values of α.

$\boldsymbol{\alpha}$	-1.53	-0.76	0	0.76	1.53	6.11	13.75
$\boldsymbol{d_{180}}$	0	137.5	275	412.5	550	1,375	2,750
% Change	-100%	-50%	0%	+50%	+100%	+400%	+900%

Table 5.1: Change in expected demand for each value of α considered with the initial demand of 275 per day.

From the sensitivity analysis of the eighty-one scenarios presented in Figure 3.4, it is determined that for seventy of the scenarios considered (86.4%) the SCS that results in the lowest Total Cost is independent of the values of α considered. The relative Total Cost of each SCS to that of the lean SCS is calculated as

$$\phi_{LL,2} = \frac{C_{SCS,2}(\tau,\delta,\psi,i) - C_{LL,2}(\tau,\delta,\psi,i)}{C_{LL,2}(\tau,\delta,\psi,i)}. \qquad (5.19)$$

Figures 5.2 and 5.3 illustrate the Total Cost percent difference of the three supply chain strategies relative to a lean SCS in two settings for the various values of α. Figure 5.2 shows that a lean SCS results in the lowest Total Cost independent of the value of α for a supply chain where the scenario is high *RMP*, high lean index, low demand forecast error, and low cost of capital. For the scenario presented in Figure 5.2, an agilean SCS is slightly more expensive than a lean SCS, while an agile SCS and a leagile SCS are over 3% more expensive. Figure 5.3 shows that an agile SCS results in the lowest Total Cost independent of the value of α for a supply chain where the scenario is low *RMP*, low lean index, high demand forecast error, and high cost of capital. For the scenario presented in Figure 5.3, an agilean SCS is nearly 1% more expensive, a leagile SCS is approximately 2% more expensive, and a lean SCS is 2%-3% more expensive than an agile SCS.

In equation (5.19) when the cost $C_{SCS,2}(\tau, \delta, \psi, i)$ is replaced by $C_{AA,2}(\tau, \delta, \psi, i)$, then $\phi_{LL,2}$ computes the cost for an agile SCS relative to a lean SCS. Similarly, when $C_{SCS,2}(\tau, \delta, \psi, i)$ is replaced by $C_{LA,2}(\tau, \delta, \psi, i)$ and $C_{AL,2}(\tau, \delta, \psi, i)$, then $\phi_{LL,2}$ is the relative cost of a leagile SCS and an agilean SCS, respectively. When the value of $\phi_{LL,2} > 0$, a lean SCS results in a lower Total Cost than the comparison SCS; and when the value of $\phi_{LL,2} < 0$, the comparison SCS results in a lower Total Cost than a lean SCS.

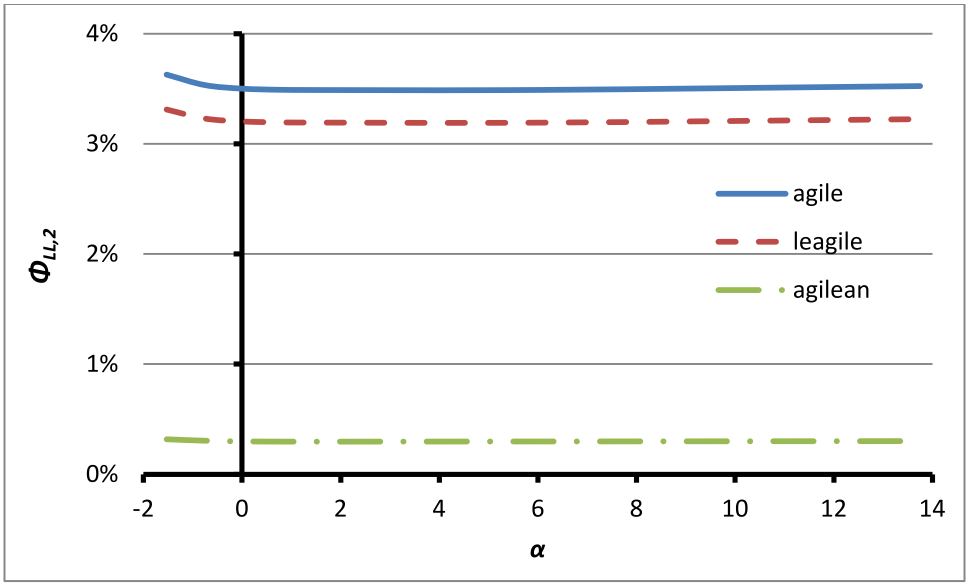


Figure 5.2: Total Cost of each SCS relative to the Total Cost for a lean SCS with high RMP, high lean index, low demand forecast error, and low cost of capital.

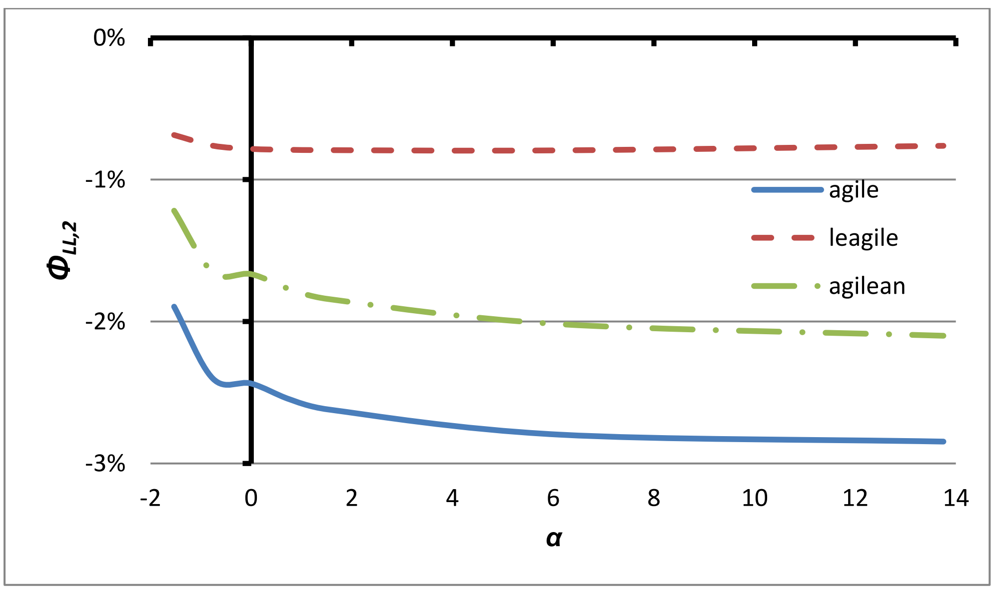


Figure 5.3: Total Cost of each SCS relative to the Total Cost for a lean SCS with low RMP, low lean index, high demand forecast error, and high cost of capital.

Figure 5.2 shows a scenario where a lean SCS results in the lowest Total Cost for the forecast period independent of whether, and how much, demand is (linearly) increasing or decreasing. In contrast, Figure 5.3 shows a scenario where an agile SCS results in the lowest Total Cost for the forecast period independent of whether, and how much, demand increases or decreases, for the values of α considered.

Figure 5.4 shows the eleven scenarios (parenthetically numbered 1 through 11) where the SCS that results in the lowest Total Cost is dependent upon the value of α. The other seventy scenarios where the SCS that results in the lowest Total Cost is independent of the value of α, and the corresponding SCS is indicated by the shading in Figure 5.4. The number in the parentheses denotes the corresponding graph in the following discussion. The SCS that results in the lowest Total Cost for each of the scenarios when $\alpha = 0$ is given by the background shading in the cell.

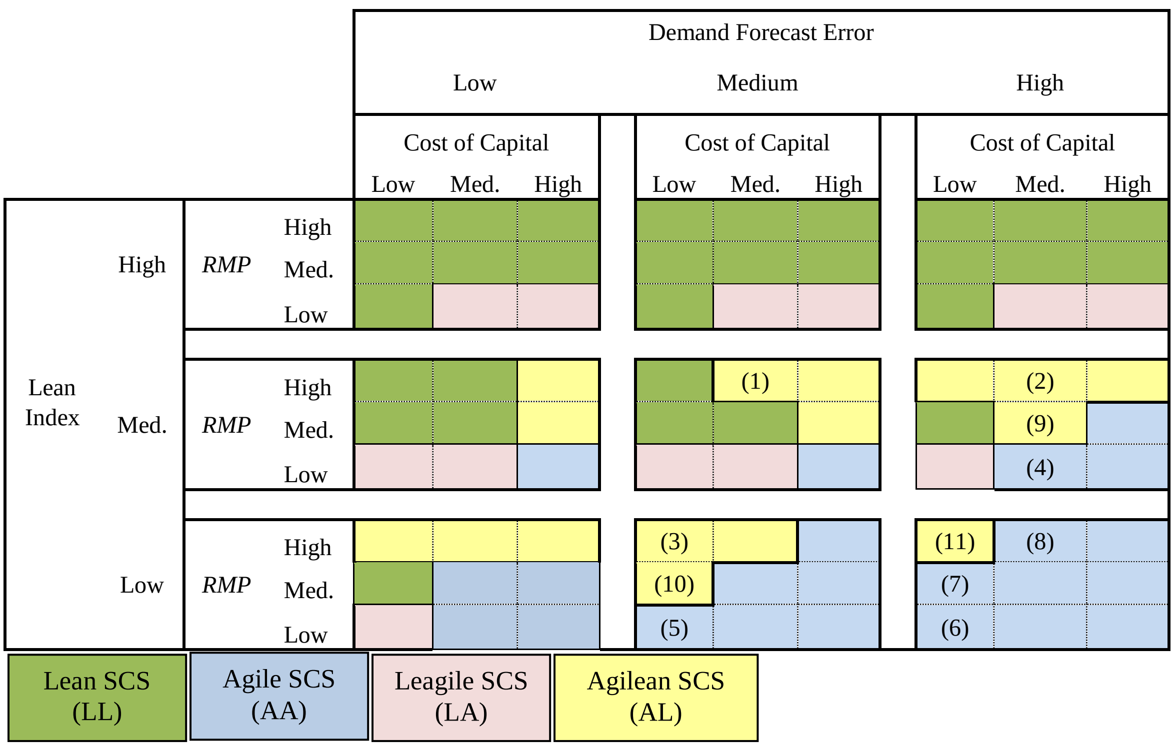
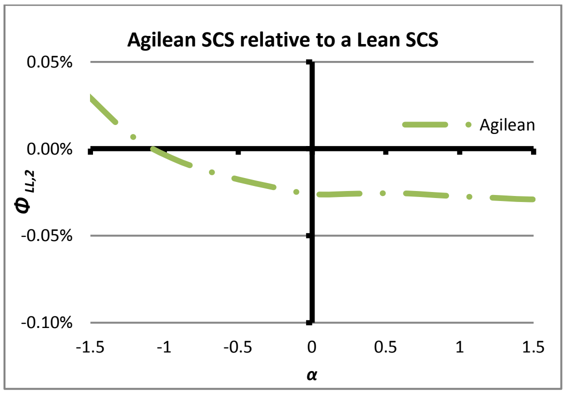


Figure 5.4: Scenarios wehre the lowest cost SCS is dependent upon the value of α.

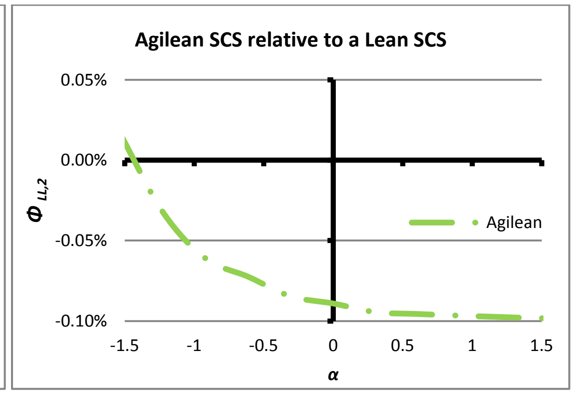
The eleven scenarios are subdivided into four groups based on which supply chain strategies provide the lowest cost: 1) an agilean SCS or a lean SCS, 2) a leagile SCS or an agile SCS, 3) an agilean SCS or an agile SCS, and 4) an agile SCS, an agilean SCS, or a lean SCS. For ease of illustration, only those supply chain strategies that result in the lowest Total Cost for a value of α are shown in Figures 5.5, 5.6, 5.7 and 5.8.

(1)



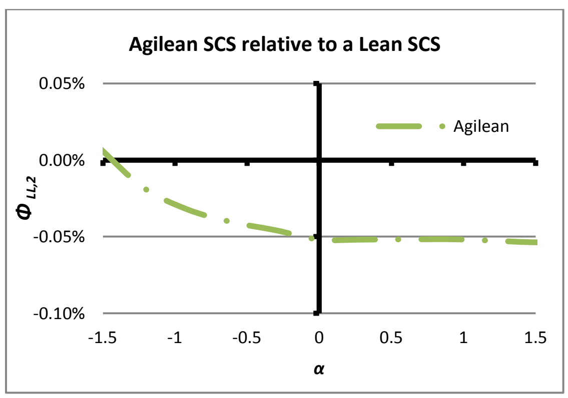
RMP-High, γ-Med., f-Med., i-Med.

(2)



RMP-High, γ-Med., f-High, i-Med.

(3)



RMP-High, γ-Low, f-Med., i-Low

Figure 5.5: Group 1: Total Cost of an agilean SCS relative to that of a lean SCS

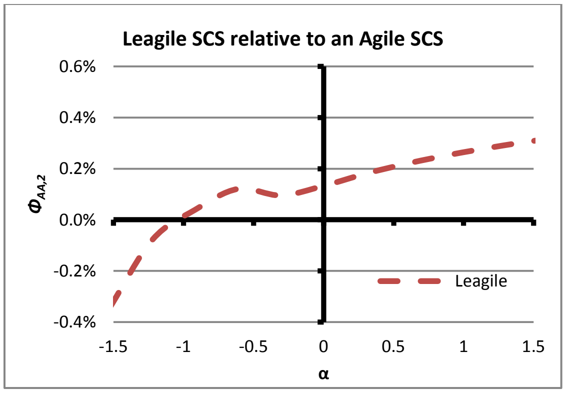
For all three scenarios depicted in Figure 5.5 a lean SCS results in a lower Total Cost when α is much less than zero. However, for all other values of α, an agilean SCS results in a lower Total Cost than the other three supply chain strategies considered. For the three scenarios presented in Figure 5.5 where the value of α is between -1.5 and 1.5, the cost difference between a lean SCS and an agilean SCS does not exceed 0.1%. Therefore, for the α values considered here one can conclude (i) using an agilean SCS and not switching to a lean SCS is at worst 0.03% more expensive and (ii) adopting a lean SCS is at most 0.1% more expensive than an agilean SCS.

For Figures 5.6 and 5.7, the relative Total Cost of each SCS are determined with respect to the Total Cost of an agile SCS,

$$\phi_{AA,2} = \frac{C_{SCS,2}(\tau,\delta,\psi,i) - C_{AA,2}(\tau,\delta,\psi,i)}{C_{AA,2}(\tau,\delta,\psi,i)}. \quad (5.20)$$

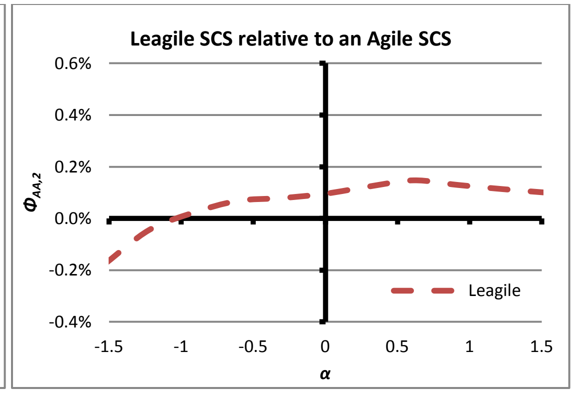
As in equation (5.19), the cost $C_{SCS,2}(\tau, \delta, \psi, i)$ in equation (5.20) is replaced by $C_{LA,2}(\tau, \delta, \psi, i)$ to determine the value of $\phi_{AA,2}$ for a leagile SCS relative to an agile SCS. Similarly, the cost $C_{SCS,2}(\tau, \delta, \psi, i)$ is replaced by $C_{AL,2}(\tau, \delta, \psi, i)$ to determine $\phi_{AA,2}$ for an agilean SCS. When the value of $\phi_{AA,2} > 0$, an agile SCS results in a lower Total Cost than the comparison SCS; and when the value of $\phi_{AA,2} < 0$, the comparison SCS results in a lower Total Cost than an agile SCS.

(4)



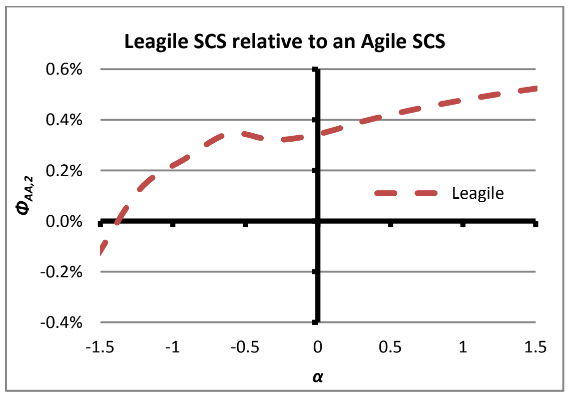
RMP-Low, γ-Med., f-High, i-Med.

(5)



RMP-Low, γ-Low, f-Med., i-Low

(6)

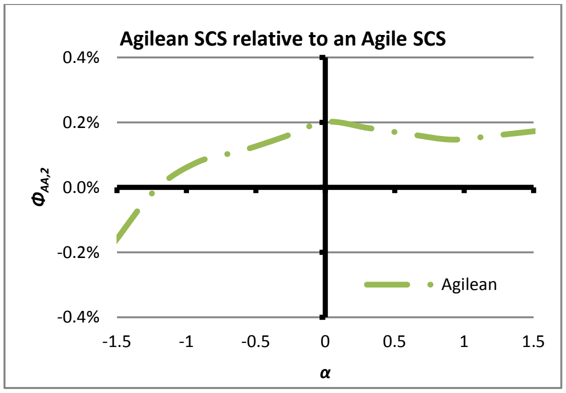


RMP-Low, γ-Low, f-High, i-Low

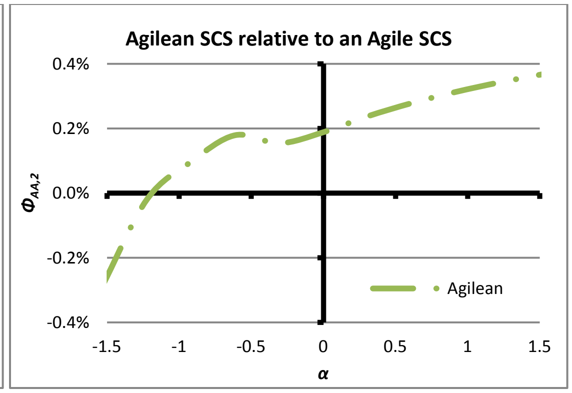
Figure 5.6: Group 2: Total Cost of a leagile SCS relative to that of an agile SCS

For all three scenarios depicted in Figure 5.6 a leagile SCS results in a lower Total Cost when α is less than -1.0 compared to an agile SCS. However, for all larger values of α, an agile SCS results in a lower Total Cost than the other three supply chain strategies. Furthermore, the financial benefit of adopting a leagile SCS never exceeded 0.6% of the Total Cost of an agile SCS for the forecast period when the value of α is between -1.5 and 1.5. Therefore, unless the cost of changing supply chain strategies is small and the expected daily demand rate is expected to decrease significantly during the forecast period, the supply chain should stay with the agile SCS.

(7)



(8)



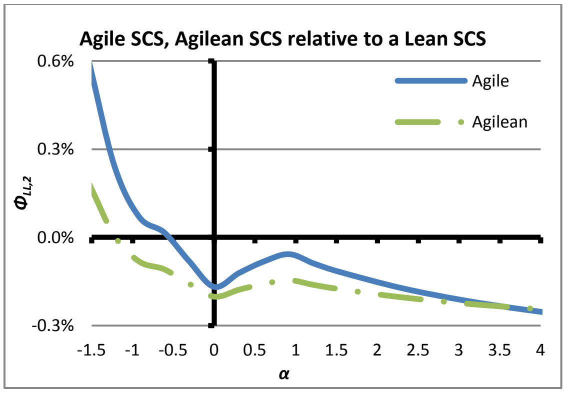
RMP-Med., γ-Low, f-High, i-Low

RMP-High, γ-Low, f-High, i-Med.

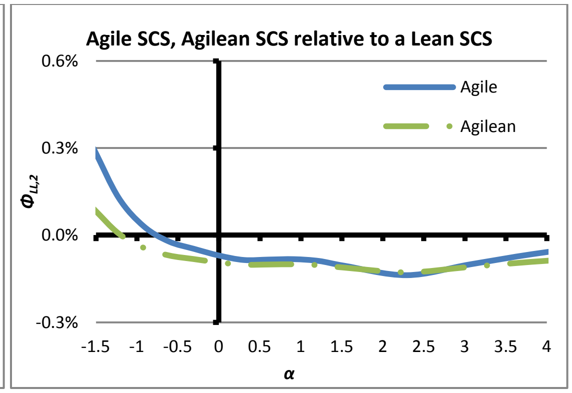
Figure 5.7: Group 3: Total Cost of an agilean SCS relative to that of an agile SCS

For both scenarios depicted in Figure 5.7, an agilean SCS results in a lower Total Cost when α is approximately -1.25 or less. However, for all other values of α, an agile SCS results in a lower Total Cost than the other three supply chain strategies considered. Furthermore, the financial benefit of adopting an agilean SCS never exceeds 0.4% of the Total Cost of an agile SCS. Therefore, unless the cost of changing supply chain strategies is small and the expected daily demand rate is expected to decrease significantly during the forecast period, the supply chain should stay with the agile SCS.

(9)



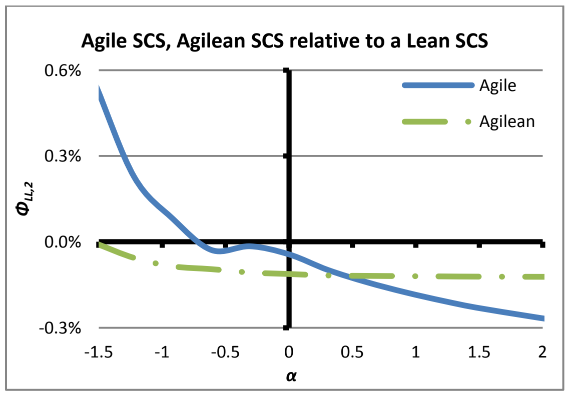
(10



RMP-Med., γ-Med., f-High, i-Med.

RMP-Med., γ-Low, f-Med., i-Low

(11



RMP-High., γ-Low, f-High, i-Low

Figure 5.8: Group 4: Agile, Agilean SCS vs. Lean SCS

The three scenarios illustrated in Figure 5.8 are the only cases identified where an α greater than zero indicates a change in the SCS results in a lower Total Cost than the SCS with the lowest Total Cost when $\alpha = 0$. In the upper left graph in Figure 5.8, when the α value is greater than approximately 3.5 an agile SCS results in a lower Total Cost than an agilean SCS. An α value of 3.5 implies the supply chain is expecting a very significant increase in expected daily demand rate during the forecast period. In the upper right graph in Figure 5.8, when α is approximately 2.5, an agile SCS results in a slightly lower Total Cost than an agilean SCS. However, an agile SCS results in the lowest Total Cost for only a small window of α values around 2.5. For all other α values greater than approximately -1.25 an agilean SCS results in a lower Total Cost. The lower graph in

Figure 5.8 is the only scenario where a change in the lowest cost SCS from the best SCS when expected daily demand rate is held constant for the forecast period $(\alpha = 0)$ occurs with an α value between -1.0 and 1.5. In this example, if the supply chain is anticipating the expected daily demand rate to increase more than 25% $(\alpha = 0.50)$ during the forecast period, then an agile SCS should be adopted to minimize the Total Cost.

5.3.2 Demand forecast error and demand changes with time

Figure 5.9 shows the twenty-seven scenarios where the the SCS that results in the lowest Total Cost is dependent upon the demand forecast error value. Often it is difficult to accurately forecast expected demand and the level of uncertainty associated with the forecast. For example, Hewlett-Packard in the 1990's found that the level of demand forecast error for a printer during its introduction stage was 80-90% and the demand forecast error improved to around 40% during the maturity stage of a printer's life cycle (Simchi-Levi et al., 2008, pg. 362). In Figure 5.9, the twenty-seven scenarios where the SCS that results in the lowest Total Cost depends on the magnitude of demand forecast error are noted by the two letter abbreviation of the SCS.

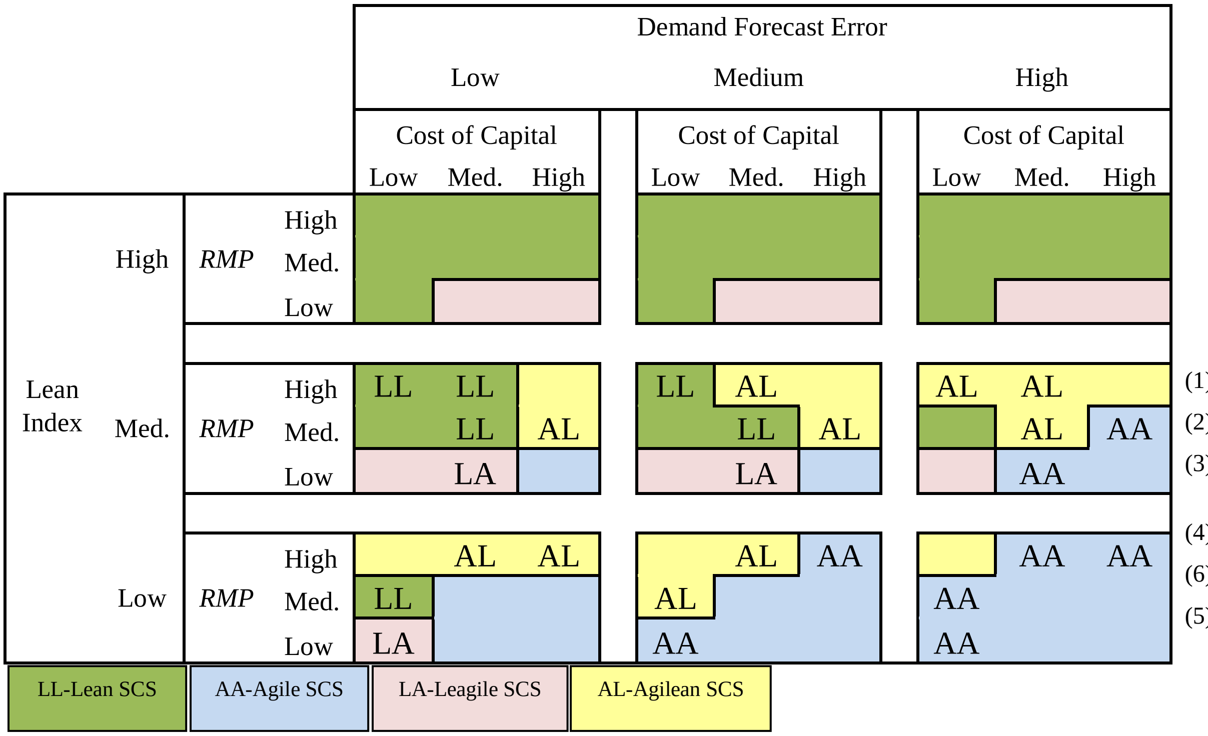
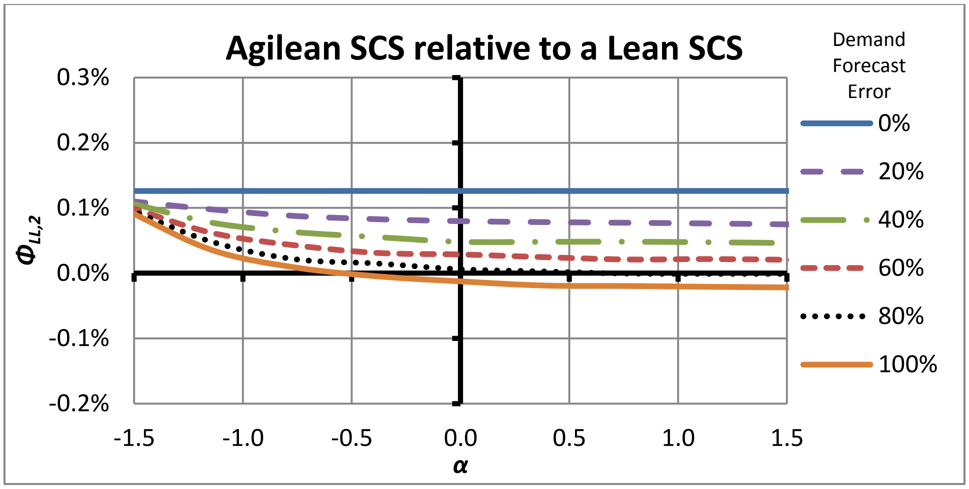
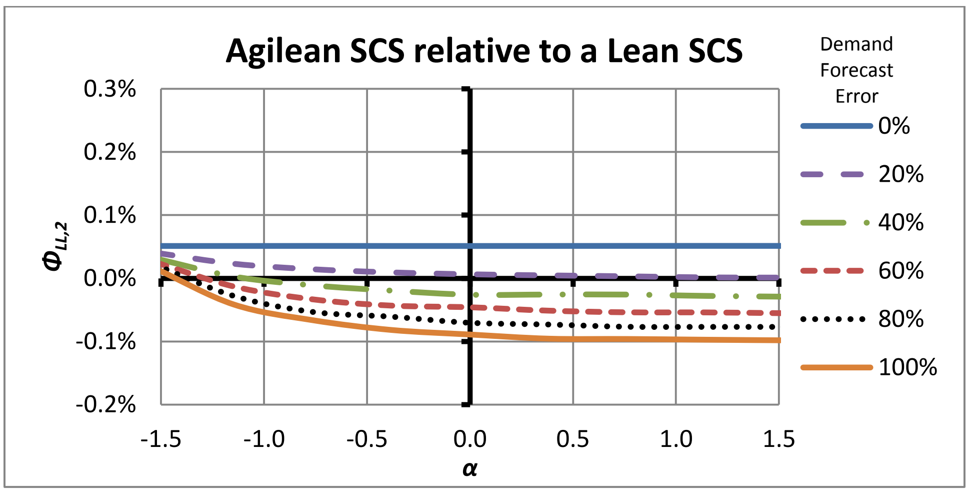


Figure 5.9: SCS was dependent upon the demand forecast error value

The twenty-seven scenarios in Figure 5.9 are partitioned into six categories (identified by a number in parenthesis to the right of Figure 5.9) based on the lean index and *RMP* value: 1) *RMP* high and lean index medium, 2) *RMP* medium and lean index medium, 3) *RMP* low and lean index medium, 4) *RMP* high and lean index low, 5) *RMP* low and lean index low, and 6) *RMP* medium and lean index low. Figures 5.10 through 5.15 illustrates the Total Cost relative to either a lean SCS or an agile SCS, accordingly, with respect to the level of demand forecast error and the anticipated change in expected daily demand rate during the forecast period, α.



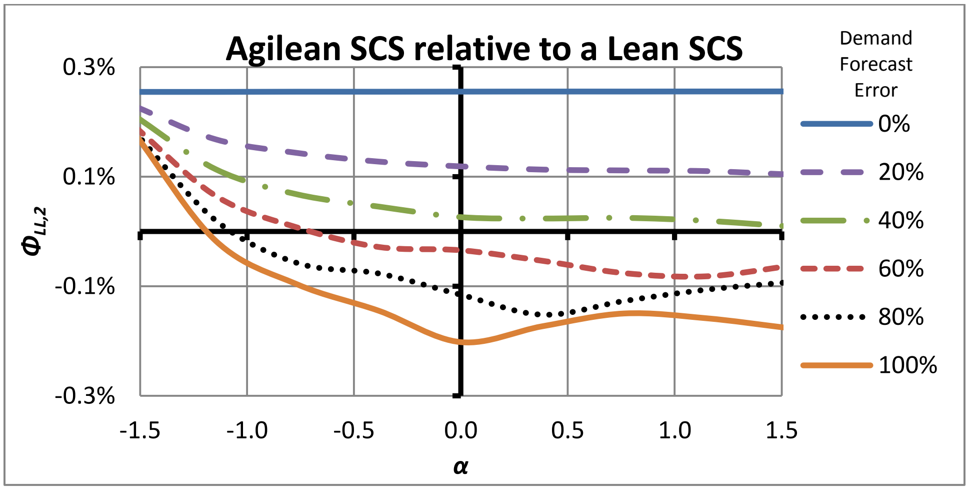
RMP-High, γ-Medium, i-Low



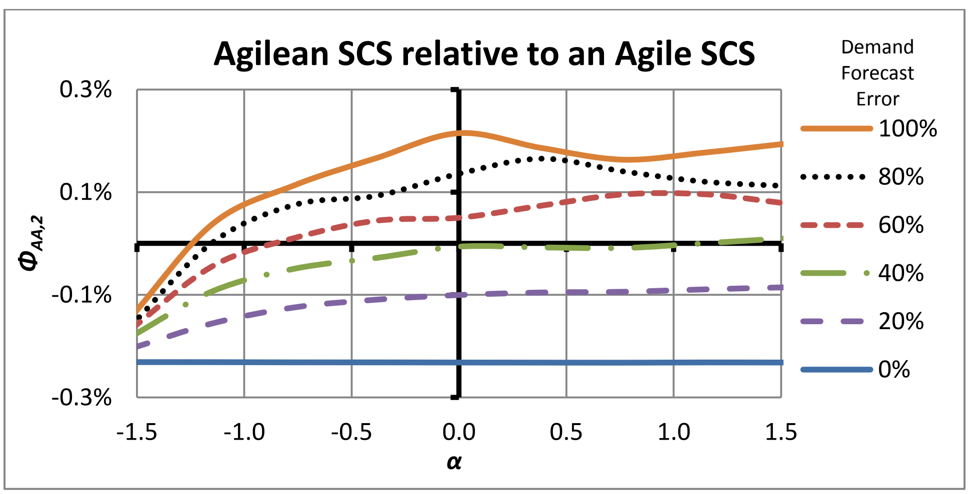
RMP-High, γ-Medium, i-Medium

Figure 5.10: Category 1 - *RMP*-High and Lean Index Medium

For Category 1, with low cost of capital (top of Figure 5.10), a lean SCS results in the lowest Total Cost for supply chains where the demand forecast error is less than 80% and when the value of α is less than approximately 0.70. However, with low cost of capital, when demand forecast error is >80%, and expected daily demand rate is stable or is expected to increase, the supply chain should consider adopting an agilean SCS to minimize Total Cost. With the cost of capital at a medium level (bottom of Figure 5.10) the supply chain should adopt a lean SCS when demand forecast error is less than 20% or the expected daily demand rate decreases significantly during the forecast period; otherwise the supply chain should employ an agilean SCS.



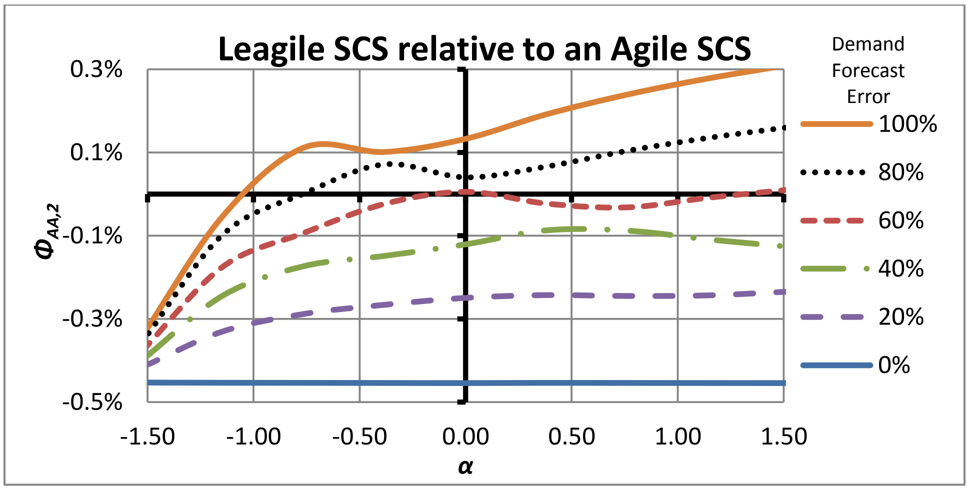
RMP-Medium, γ-Medium, i-Medium



RMP-Medium, γ-Medium, i-High

Figure 5.11: Category 2 - *RMP*-medium and lean index medium

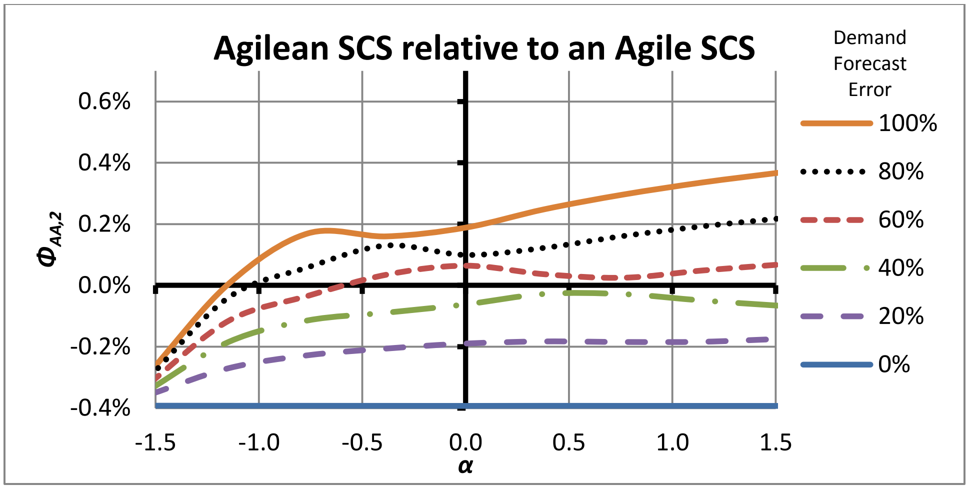
For Category 2, with medium cost of capital (top of Figure 5.11), a lean SCS should be adopted when demand forecast error is 40% or less or when the expected daily demand rate is anticipated to decrease significantly. However, when the demand forecast error is greater than 40% and the level of expected daily demand rate is stable or increasing for the forecast period, then the supply chain should adopt an agilean SCS. When the cost of capital is at a high level (bottom of Figure 5.11), the supply chain should adopt an agile SCS when demand forecast error is greater than 40% and the expected daily demand rate is stable or increasing; otherwise the supply chain should consider adopting an agilean SCS.



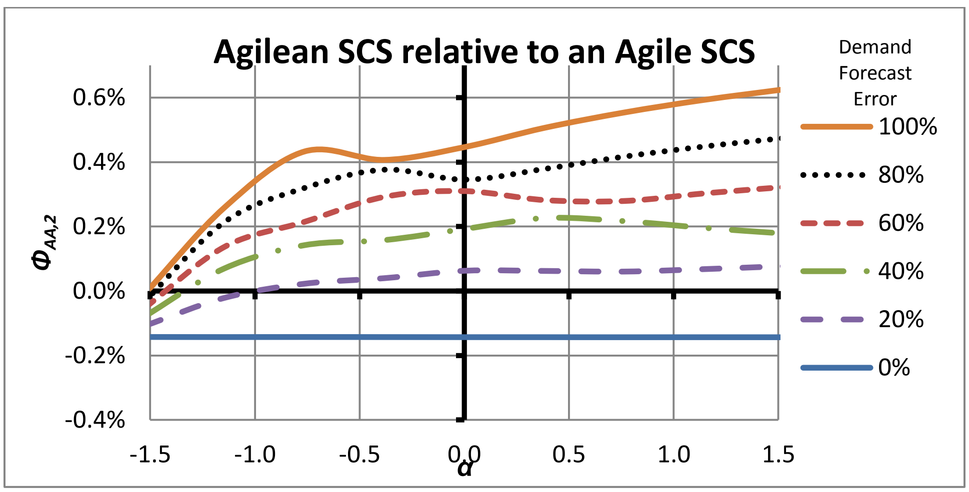
RMP-Low, γ-Medium, i-Medium

Figure 5.12: Category 3 - *RMP*-low and lean index medium

For Category 3, Figure 5.12 shows that an agile SCS should be employed when the demand forecast error is greater than 60% and the expected daily demand rate is nearly stable or increasing, and a leagile SCS should be adopted when the demand forecast error is less than 60% or when the expected daily demand rate decreases significantly during the forecast period.



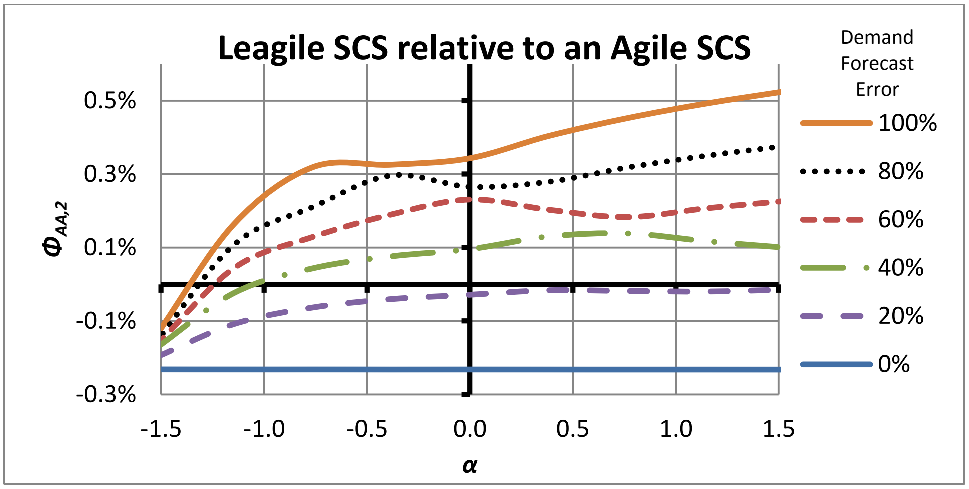
RMP-High, γ-Low, i-Medium



RMP-High, γ-Low, i-High

Figure 5.13: Category 4 - *RMP*-high and lean index-low

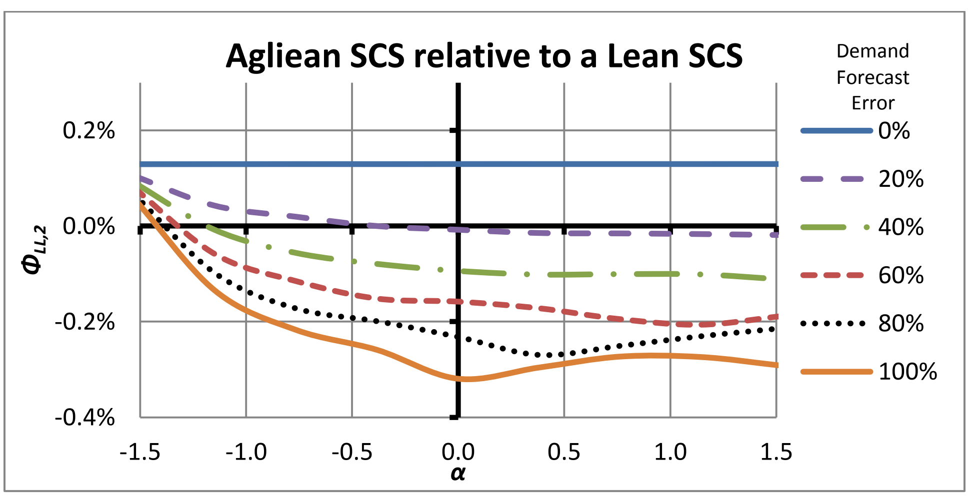
For Category 4, when the cost of capital is medium (top of Figure 5.13), the supply chain should adopt an agile SCS when demand forecast error is greater than 60% and the value of α is larger than approximately -0.50 and adopt an agilean SCS when demand forecast error is less than 40%. With high cost of capital (bottom of Figure 5.13), an agilean SCS will only result in a lower Total Cost relative to an agile SCS when the demand forecast error is less than approximately 15% and the value of α is less than -1.0.

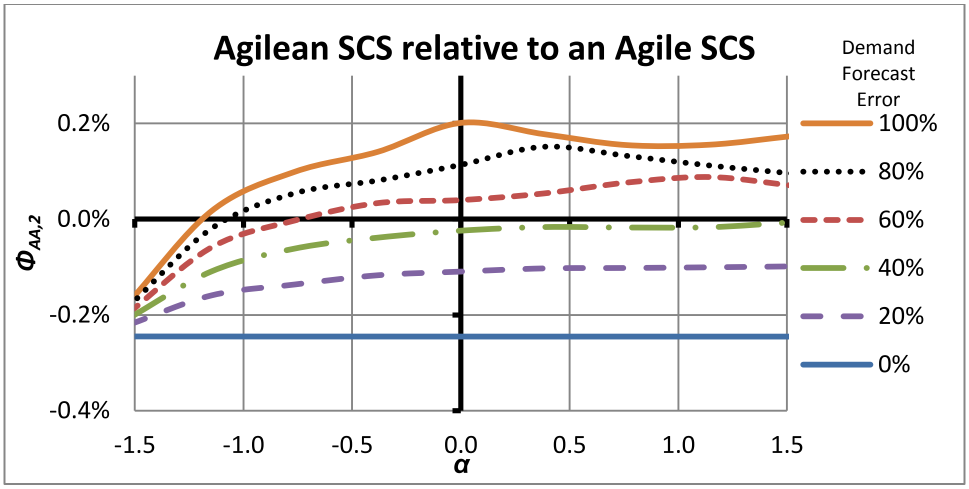


RMP-Low, γ-Low, i-Low

Figure 5.14: Category 5 - *RMP*-low and lean index-low

For Category 5, illustrated in Figure 5.14 (low *RMP*, low lean index, and low cost of capital), the supply chain should adopt an agile SCS when demand forecast error is greater than approximately 20% and the value of α is larger than 0, and a leagile SCS when demand forecast error is less than 20%. Otherwise, the SCS that results in the lowest Total Cost, either leagile SCS or agile SCS, is dependent on the value of demand forecast error and the value of α.





RMP-Medium, γ-Low, i-Low

Figure 5.15: Category 6 - *RMP*-medium and lean index-low

Finally, Category 6 depicted in Figure 5.15 (medium *RMP*, low lean index, and low cost of capital), includes the only scenarios examined where the SCS that results in the lowest Total Cost is different at all three levels of demand forecast error considered in Figure 3.4. When the expected demand forecast error increases from low to medium the SCS which minimizes Total Cost changes from lean SCS to an agilean SCS, and then when the expected demand forecast error increases to a high level the SCS that minimizes Total Cost is an agile SCS. From Figure 5.15, a lean SCS minimizes Total Cost when demand forecast error is approximately 18% or less, independent of the value of α. An agilean SCS should be implemented when the demand forecast error ranges from approximately 18% to 40% and the value of α is greater than -1.0. An agile SCS should be adopted when the demand forecast error is greater than 60% and the value of α is greater than -0.75. The SCS that results in the lowest Total Cost for those supply chains with medium *RMP*, low lean index, low cost of capital, and when the level of demand forecast error and the value of α are not one of the three combinations presented, needs to be evaluated on a case by case basis.

5.4 Summary

The two purposes of this chapter were to determine the SCS that resulted in the lowest Total Cost for the various scenarios considered and to examine the sensitivity of the lowest cost SCS selected to changes in aspects of expected demand. Figure 5.16 expands the cubes from Figure 3.4 and identifies the appropriate SCS that minimizes Total Cost for each scenario, assuming the baseline supply chain setting presented in Chapter 4. From Figure 5.16, a leagile SCS should be considered when the structure of the supply chain is such that the vast majority of production costs are incurred at the supplier (low *RMP*) and an agilean SCS should be considered when the structure of the supply chain is such that the majority of production costs are incurred at the manufacturer (high *RMP*) and lean index is low or medium.

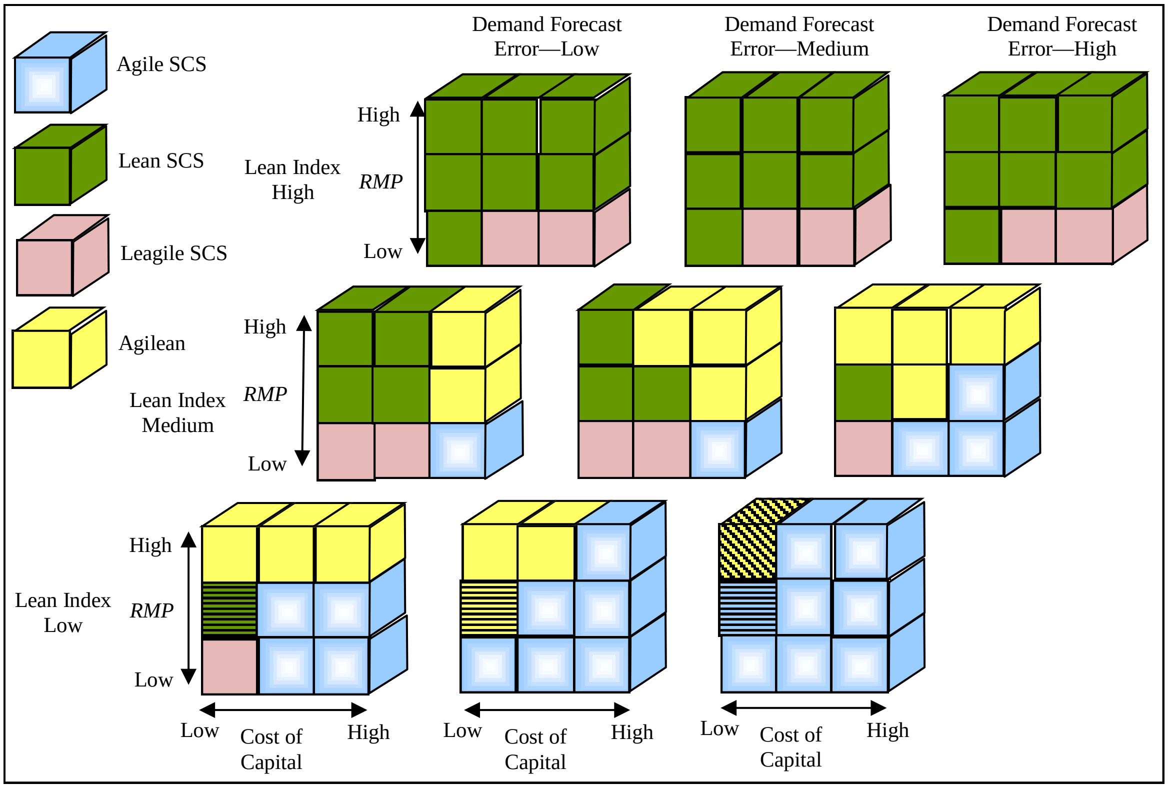


Figure 5.16: The SCS which results in the lowest Total Cost for all scenarios considered.

The sensitivity analysis of SCS selection with respect to an anticipated increase or decrease in expected demand during the forecast period shows that for the majority of scenarios considered (86.4%) the SCS that results in the lowest Total Cost is independent of a change in the expected demand level during the forecast period. For each of the groups where the SCS that results in the lowest Total Cost is dependent on the anticipated change in expected daily demand rate during the forecast period, when a considerable decrease in expected demand is anticipated a leaner SCS may result in a lower Total Cost. For example, scenarios in Group 1 would move from an agilean SCS to a lean SCS, Group 2 would move from an agile SCS to a leagile SCS, Group 3 would move from an agile SCS to an agilean SCS, and Group 4 would move from an agilean SCS to a lean SCS. The analysis shows that generally the appropriate SCS to minimize Total Cost when the anticipated change in expected daily demand rate over the forecast period is between -50% to +100% is the same as when expected daily demand rate is constant for the forecast period; therefore, the simpler model presented in Chapter 4 might be sufficient for determining the SCS that minimizes Total Cost for the supply chain. The single scenario where the SCS that results in the lowest Total Cost changes when the change in expected daily demand rate is between -50% to +100% occurs with high *RMP*, low lean index, low cost of capital and high demand forecast error, the cube shaded by diagonal lines in Figure 5.16. This analysis assumes the initial expected demand is 275 units per day and further analysis would be needed to determine the range of demand values where these findings are generalizable.

The analysis of the sensitivity of the lowest Total Cost SCS for the forecast period with respect to the level of demand forecast error shows that when the lean index is high, the lowest cost SCS is independent of the demand forecast error level. When the lean index and the cost of capital are both medium, the SCS that results in the lowest Total Cost is dependent on the demand forecast error level for the values of *RMP* considered here. For the scenarios with low lean index, medium *RMP*, and the low cost of capital, shown by the cubes shaded by horizontal lines in Figure 5.16, the SCS that results in the lowest Total Cost changes at each level of demand forecast error considered.

6. Supply chain strategy selection for product life cycle

The question addressed by this chapter is Q3: Under what combination of supply chain characteristics does each SCS minimize total supply chain cost over the life cycle of a product?

This chapter uses the term "simple SCS" to denote the situation where the SCS is not allowed to change over the PLC. The term "complex SCS" is used to denote the situation where the SCS is allowed to change during the PLC. For some scenarios where the SCS does not change over the PLC, the complex SCS is the same as the simple SCS. The primary purpose of this chapter is to (i) determine which SCS results in the lowest Total Cost over the product life cycle when the SCS does not change over the PLC (simple SCS), and (ii) determine the impact on the Total Cost of using a simple SCS versus allowing the SCS to change during the PLC (complex SCS).

6.1 Problem description

The classical PLC, shown in Figure 6.1, includes four stages: introduction, growth, maturity, and decline. For products in the introduction stage of the PLC there is a high level of uncertainty associated with the expected market response and the diffusion rate of the product in the market, which results in a low level of demand predictability and a high level of demand forecast error. In the growth stage, products experience an increase in unit sales per time period but at a diminishing rate as competing products eventually enter the market and the saturation level of the product in the market increases. At the maturity stage of the PLC, the demand rate is at its highest level and the predictability of demand has improved resulting in a lower level of demand forecast error.

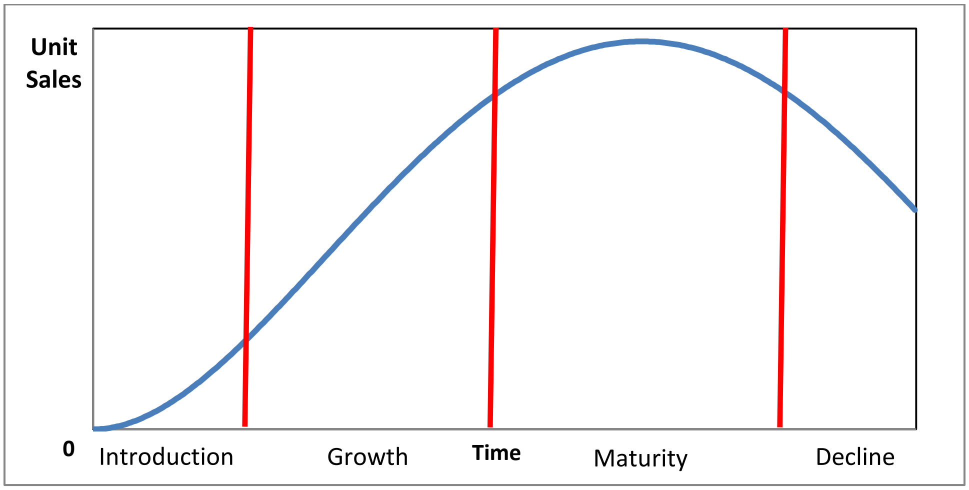


Figure 6.1: Classical product life cycle (Source: Rink and Swan, 1979)

The literature does not include a general function for the classical PLC model; however, the PLC can be modeled as a 4th degree polynomial. For this dissertation, the following assumptions are made concerning the classical PLC function: (i) it describes the expected demand as a function of time, $d(t)$, (ii) the PLC is a 4th degree polynomial, (iii) the function intersects the horizontal axis in exactly two places, at $t = 0$ and $t = T_F$, and (iv) no point along the function lies below the horizontal axis, $d(t) \geq 0 \ \forall \ t = [0, T_F]$. The general expression for the PLC is then

$$d(t) = a_1 t^4 + a_2 t^3 + a_3 t^2 + a_4 t + a_5, \tag{6.1}$$

and with the assumptions from the previous paragraph, the PLC may be further simplified to

$$d(t) = a_1 t^4 - 2\sqrt{a_1 a_3} t^3 + a_3 t^2. \tag{6.2}$$

The continuous expected demand function, equation (6.2), is discretized to the expected daily demand d_j for $j = 1, 2, \ldots, T_F$, where $d_0 = 0$ as

$$d_j = \int_{j-1}^{j} d(t)\,dt = \left(\frac{a_1\left(j^5-(j-1)^5\right)}{5} - \frac{\sqrt{a_1 a_3}\left(j^4-(j-1)^4\right)}{2} + \frac{a_3\left(j^3-(j-1)^3\right)}{3}\right)$$

$$\forall\, j = 1, 2, \ldots, T_F \quad (6.3)$$

As shown in Figure 6.1, during the decline stage of the PLC the demand for the product decreases with respect to time and a product is typically discontinued at some point. This dissertation denotes the point in time where the product is discontinued as T, where

$$T = \frac{3(T_F)}{4}. \quad (6.4)$$

This dissertation considers only demand prior to time T as depicted in Figure 6.2.

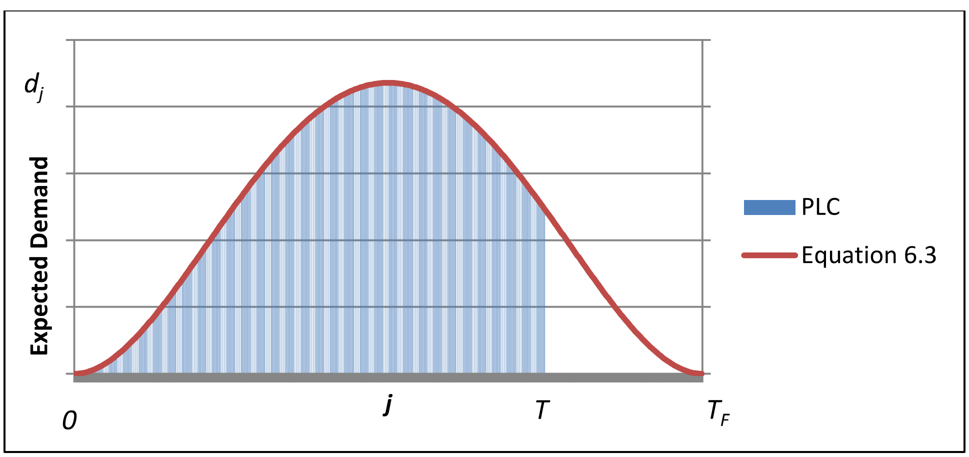


Figure 6.2: Classical PLC from $[0, T]$.

The classical PLC from $[0, T]$with PLC stages is depicted in Figure 6.3.

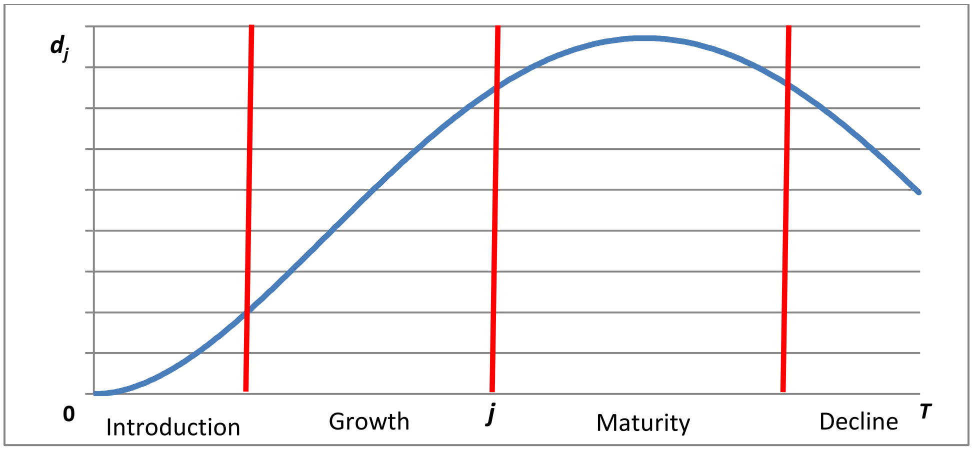


Figure 6.3: Classical PLC from $[0, T]$ with PLC stages.

For a given total expected demand for a product, D_T, over the PLC $[0, T]$, the values of a_1 and a_3 are determined by setting equation (6.2) equal to zero and solving for t:

$$d(T_F) = 0,$$

$$T_F = \frac{\sqrt{a_3}}{\sqrt{a_1}} \tag{6.5}$$

or, using equation 6.4,

$$a_3 = a_1 {T_F}^2 = \frac{16}{9} a_1 T^2. \tag{6.6}$$

The parameter a_1 can be expressed in terms of total expected demand over the PLC, D_T, and the length of the PLC, T, by substituting equation (6.6) into equation (6.2) and solving the following expression

$$D_T = a_1 \int_0^T t^4 - \frac{8}{3} T t^3 + \frac{16}{9} T^2 t^2$$

$$D_T = a_1\left(\frac{T^5}{5} - \frac{8}{3}T\frac{T^4}{4} + \frac{16}{9}T^2\frac{T^3}{3}\right)$$

$$a_1 = \frac{135D_T}{17T^5}. \tag{6.7}$$

The expected daily demand d_j in terms of total expected demand, D_T, and the length of the PLC, T, is determined by substituting equations (6.6) and (6.7) into equation (6.3),

$$d_j = \left(\frac{27D_T\left(j^5-(j-1)^5\right)}{17T^5} - \frac{90D_T\left(j^4-(j-1)^4\right)}{17T^4} + \frac{80D_T\left(j^3-(j-1)^3\right)}{17T^3}\right). \qquad \forall\, j = 1, 2, \dots, T \tag{6.8}$$

This research assumes that the PLC is subdivided into Q nonoverlapping sequential time periods, denoted as epochs, and each epoch is T_Q in length, so that

$$T = QT_Q. \tag{6.9}$$

The modification of the Total Cost function employed in this chapter to determine the Total Cost over the life-cycle of a product employs a rolling horizon perspective. A rolling horizon perspective invokes a solution method where an initial solution is determined for the first epoch of the PLC (starting at time 0). The ending position from the initial epoch is then used to determine the optimal solution to the next epoch of the PLC. This process is repeated until a solution had been determined for all epochs of the PLC.

The rolling horizon heuristic allows the number of order periods to vary between epochs and thus to change over the PLC. With a simple SCS, the same SCS is used for all epochs of the PLC, the supply side and the demand side service levels and lead times are constant for all epochs of the PLC, but the number of order periods per epoch may differ between epochs of the PLC. With a complex SCS, the SCS may change during the PLC, so the supply side and demand side service levels and lead times which are dependent on the SCS selected for each epoch may differ between epochs of the PLC. With a complex SCS, the number of supply side and demand side order periods may also differ between epochs.

The epochs of the PLC are indexed by $q = 1, 2, \dots, Q$. The number of demand side order periods for an epoch of the PLC is denoted by N_{D_q}. Similarly, for the supply side the number of order periods for an epoch of the PLC is denoted by N_{S_q}. The set of possible values for N_{D_q} is taken as a positive integer $[1, T_Q]$, such that $\frac{T_Q}{N_{D_q}}$ is an integer. Therefore, the minimum value for N_{D_q} is 1 and the maximum value for N_{D_q} is T_Q. The set of possible values for N_{S_q} is defined similarly so that $\frac{T_Q}{N_{S_q}}$ is an integer. The individual demand side orders for epoch q are indexed by $n_D = 0, 1, 2, \dots, N_{D_q}$ and the individual supply side orders for epoch q are indexed by $n_S = 0, 1, 2, \dots, N_{S_q}$. When T_Q is large, the set of possible values for N_{S_q} and N_D may include many values. For example, when $T_Q = 90$ the set includes $\{1, 2, 3, 4, 5, 6, 9, 10, 15, 18, 30, 45, 90\}$. Order n_D of epoch q is for the expected demand plus safety stock requirements for the order period from day $j_{q,(n_D-1)} + 1$ to j_{q,n_D}, where j_{q,n_D} is given by

$$j_{q,n_D} = T_Q\left(\frac{n_D}{N_{D_q}} + q - 1\right). \quad \forall n_D = 1, \dots, N_{D_q}, \forall q = 1, \dots, Q \quad (6.10)$$

Order n_D of epoch q will arrive at the customer at time $j_{q(n_D-1)}$. The length of each order period n_D of epoch q is

$$\frac{T_Q}{N_{D_q}}. \quad (6.11)$$

The demand side costs of order n_D of epoch q are incurred at time

$$j_{q,(n_D-1)} - L_D. \quad (6.12)$$

Similarly, order n_S of epoch q is the expected demand plus safety stock requirements for the order period from time $j_{q,(n_S-1)} + 1$ to j_{q,n_S}, where j_{q,n_S} is given by

$$j_{q,n_S} = T_Q\left(\frac{n_S}{N_{S_q}} + q - 1\right). \quad \forall n_S = 1, \dots, N_{S_q}, \forall q = 1, \dots, Q \quad (6.13)$$

Order n_S arrives at the customer at time $j_{q,(n_S-1)}$. The length of each order period n_S of epoch q is

$$\frac{T_Q}{N_{S_q}}. \quad (6.14)$$

The supply side costs of order n_S of epoch q are incurred at time

$$j_{q,(n_S-1)} - L_D - L_S. \quad (6.15)$$

As Rinker (1979) discussed, the demand variability of a product that exhibited the classical PLC tends to reduce with time. To capture this aspect of the classical PLC, demand forecast error is modeled as an exponential decay function of time,

$$f(t) = ae^{\frac{-xt}{T_F}} + b. \quad (6.16)$$

The x parameter in equation (6.16) is a decay factor that allows the impact of the rate at which demand variability decreases over the PLC to be examined. To determine the value of coefficients a and b in equation (6.16), this dissertation assumes that the initial value for demand forecast error at time zero is known and that the demand forecast error at time T_F is zero. The values of a and b are determined by solving equation (6.6) for $f(0)$ and $f(T_F)$ simultaneously, where $a = \frac{-f(0)}{e^{-x}-1}$ and $b = f(0)\left(1 + \frac{1}{e^{-x}-1}\right)$. The resulting decay function for demand forecast error for the forecast period $[0, T_F]$, expressed in terms of the demand forecast error at time zero and the length of the PLC, where $f(0) \geq 0$ and $x > 0$, is

$$f(t) = f(0)\left(1 + \frac{1}{e^{-x}-1} - \frac{e^{\frac{-3xt}{4T}}}{e^{-x}-1}\right). \qquad (6.17)$$

The demand forecast error function is discretized in terms of days from 0 to T, where $f(0) = f_0$ and

$$f_j = \int_{j-1}^{j} f(t)\, dt = f_0\left(\frac{x - \frac{4}{3}T\left(e^{\left(\frac{3x}{4T}\right)}-1\right)e^{\left(x-\frac{3xj}{4T}\right)}}{x(1-e^{x})}\right). \qquad \forall\, j = 1, 2, \ldots, T \quad (6.18)$$

Realized demand $\hat{d}_j$ is assumed to be normally distributed about expected demand d_j for the life cycle of the product; $N\left[d_j, \left(\sigma_d(j)\right)^2\right]$. Expected demand, realized demand and the demand forecast error are presumed constant for each day j and the expected daily demands are assumed mutually independent. The standard deviation of realized demand about expected demand is defined by substituting equations (6.8) and (6.18) into equation (3.15),

$$\sigma_j = \frac{f_j * d_j}{0.6745}. \qquad \forall\, j = 1, 2, \ldots, T \quad (6.19)$$

The standard deviation of the cumulative distribution function (CDF) of expected demand for each order period is the square root of the summation of the expected demand variances for the entire order period. The CDF for the demand side of the supply chain is determined by

$$\sigma_{q,n_D} = \sqrt{\sum_{j=j_{q,(n_D-1)}+1}^{j_{q,n_D}} \sigma_j{}^2}. \quad \forall n_D = 1, \ldots, N_{D_q}, \forall q = 1, \ldots, Q \quad (6.20)$$

The CDF for the supply side of the supply chain is determined by

$$\sigma_{q,n_S} = \sqrt{\sum_{j=j_{q,(n_S-1)}+1}^{j_{q,n_S}} \sigma_j{}^2}. \quad \forall n_S = 1, \ldots, N_{S_q}, \forall q = 1, \ldots, Q \quad (6.21)$$

The safety stock inventory levels for each order period, n_D and n_S, of epoch q with supply chain strategy X are

$$Z_{X,D_q}\sigma_{q,n_D} \qquad \forall q = 1, \ldots, Q \quad (6.22)$$

and

$$Z_{X,S_q}\sigma_{q,n_S}. \qquad \forall q = 1, \ldots, Q \quad (6.23)$$

The demand side safety stock inventory level at the start of the initial epoch of the PLC, where $q = 1$ and $n_D = 0$, is assumed to be zero, and is given by

$$Z_{X,D_1}\sigma_{1,0} = 0 \quad (6.24)$$

For subsequent epochs of the PLC, the demand side initial safety stock inventory level of the epoch, for $q > 1$ and $n_D = 0$, is the expected safety stock inventory level of the last order period of the previous epoch, given by

$$Z_{X,D_q}\sigma_{q,0} = Z_{X,D_{(q-1)}}\sigma_{(q-1),N_{D_{(q-1)}}}. \quad q = 2, 3, \dots, Q \quad (6.25)$$

The supply side safety stock inventory level at the start of the initial epoch of the PLC, where $q = 1$ and $n_S = 0$, is assumed to be zero, and is given by

$$Z_{X,S_1}\sigma_{1,0} = 0 \quad (6.26)$$

For subsequent epochs of the PLC, the supply side safety stock inventory level at the beginning of each epoch, when $q > 1$ and $n_S = 0$, is the safety stock inventory level of the last order period of the previous epoch, given by

$$Z_{X,S_q}\sigma_{q,0} = Z_{X,S_{(q-1)}}\sigma_{(q-1),N_{S_{(q-1)}}}. \quad q = 2, 3, \dots, Q \quad (6.27)$$

The safety stock inventory ordered in each order period is the difference between the safety stock inventory level of the current order period and the previous order period. The change in safety stock inventory level from the previous order period to the next order period for the demand side is

$$Z_{X,D_q}\sigma_{q,n_D} - Z_{X,D_q}\sigma_{q,(n_D-1)}. \quad (6.28)$$

The change in safety stock inventory level from the previous order period to the next order period for the supply side is

$$Z_{X,S_q}\sigma_{q,n_S} - Z_{X,S_q}\sigma_{q,(n_S-1)}. \quad (6.29)$$

The PLC Total Cost function when expected demand mimics a classical PLC and demand forecast error improves with time, denoted $C_3(\tau, \delta, \psi, i)$, is the summation of the Total Cost for each epoch of the PLC. The PLC Total Cost for a complex SCS is developed by substituting equations (6.3), (6.28), and (6.29) into equation (3.32) and summing over all epochs,

$$C_3(\tau, \delta, \psi, i) =$$

$$e^{i(L_{X,S}+L_{X,D})} \sum_{q=1}^{Q} \left[\sum_{n_S=1}^{N_{S_q}} \left(K_X \left\{ \left(\sum_{j=j_{q,(n_S-1)}+1}^{j_{q,n_S}} d_j \right) + Z_{X,S_q} \sigma_{q,n_S} - Z_{X,S_q} \sigma_{q,(n_S-1)} \right\} + O_S \right) e^{-i\left(j_{q,(n_S-1)}\right)} \right] +$$

$$e^{i(L_{X,D})} \left[\sum_{n_D=1}^{N_{D_q}} \left(M_X \left\{ \left(\sum_{j=j_{q,(n_D-1)}+1}^{j_{q,n_D}} d_j \right) + Z_{X,D_q} \sigma_{q,n_D} - Z_{X,D_q} \sigma_{q,(n_D-1)} \right\} + O_D \right) e^{-i\left(j_{q,(n_D-1)}\right)} \right].$$

(6.30)

The attributes $\tau, \psi,$ and i are the same as defined in the general Total Cost function $C(\tau, \delta, \psi, i)$, equation (3.26). The parameters included in the attribute group, δ, when expected demand mimics a classical PLC and demand forecast error improves with time during the PLC are: expected demand d_j, as determined from the total expected demand D_T and the parameter α_1; the standard deviation of the CDF for epoch q, σ_{q,n_D} and σ_{q,n_S}, as determined from the demand forecast error f_j and the standard deviation of demand σ_j; the length of each epoch T_Q; and the length of the PLC T. Thus $\delta = \left[d_j, D_T, \alpha_1, \sigma_{q,n_D}, \sigma_{q,n_S}, f_j, \sigma_j, T_Q, T\right]$.

As in chapter 4, the total demand side and supply side order processing cost for each epoch of the PLC is a special case of a geometric series where the partial sum is given by equation (4.12) and expressed by

$$O_D \sum_{q=1}^{Q} \sum_{n_D=1}^{N_{D_q}} e^{-i\left(j_{q,(n_D-1)}\right)} = O_D \sum_{q=1}^{Q} \frac{\left(1-e^{-iT_Q}\right)}{\left(1-e^{\frac{-iT_Q}{N_{D_q}}}\right)} e^{-iT_Q(q-1)} \qquad (6.31)$$

and

$$O_S \sum_{q=1}^{Q} \sum_{n_S=1}^{N_S} e^{-i\left(j_{q,(n_S-1)}\right)} = O_S \sum_{q=1}^{Q} \frac{\left(1-e^{-iT_Q}\right)}{\left(1-e^{\frac{-iT_Q}{N_{S_q}}}\right)} e^{-iT_Q(q-1)}. \qquad (6.32)$$

Let $u_{T_Q} = \frac{\left(1-e^{-iT_Q}\right)}{\left(1-e^{\frac{-iT_Q}{N_{S_q}}}\right)}$ and $v_{T_Q} = \frac{\left(1-e^{-iT_Q}\right)}{\left(1-e^{\frac{-iT_Q}{N_{D_q}}}\right)}$.

Equations (6.31) and (6.32) are substituted into equation (6.30); therefore, the PLC Total Cost for a complex SCS is

$$C_3(\tau, \delta, \psi, i) =$$

$$e^{i(L_{X,S}+L_{X,D})} \sum_{q=1}^{Q} \left[\sum_{n_S=1}^{N_{S_q}} \left(K_X \left\{ \left(\sum_{j=j_{q,(n_S-1)}+1}^{j_{q,n_S}} d_j \right) + Z_{X,S_q}\sigma_{q,n_S} - Z_{X,S_q}\sigma_{q,(n_S-1)} \right\} \right) e^{-i\left(j_{q,(n_S-1)}\right)} + \right.$$

$$\left. O_S u_{T_Q} e^{-iT_Q(q-1)} \right] +$$

$$e^{i(L_{X,D})} \left[\sum_{n_D=1}^{N_{D_q}} \left(M_X \left\{ \left(\sum_{j=j_{q,(n_D-1)}+1}^{j_{q,n_D}} d_j \right) + Z_{X,D_q}\sigma_{q,n_D} - Z_{X,D_q}\sigma_{q,(n_D-1)} \right\} \right) e^{-i\left(j_{q,(n_D-1)}\right)} + \right.$$

$$\left. O_D v_{T_Q} e^{-iT_Q(q-1)} \right]. \qquad (6.33)$$

6.2 Scenario analysis

To identify the SCS which minimizes Total Cost over the life cycle of a product, the scenario analysis considers the combinations of three PLC lengths (1 year, 2 years, and 5 years) and two values for total expected demands (100,000 and 1,000,000 units) for a total of six product situations. It is assumed the length of each epoch of the PLC is $T_Q = 90$ days and each year has 360 days. As in chapters 4 and 5, the lean SCS total production cost $K_L + M_L$ to deliver a single product to the customer is \$100, the ordering cost O_S and O_D are both \$200, and the lean index for the supply side and demand side are equal, $\gamma = \beta$. The demand forecast error is assumed to improve over the course of the PLC following equation (6.18) and the parameters used to describe the low, medium, and high levels are based on values of demand forecast error for a functional and an innovative product from Fisher (1997), given in Table 6.1.

Demand Characteristics	Functional	Innovative
Product life cycle	>= 2 years	3 months to 1 year
Contribution margin	5% to 20%	20% to 60%
Product variety	Few	Many
Average forecast error	10%	40% to 100%
Average stockout	1% to 2%	10% to 40%
Quantity sold at discount	0%	10% to 25%
Lead time for made to order	6 months to 1 year	1 day to 2 weeks

Source: Fisher, 1997

Table 6.1: Characteristics of functional and innovative products:

Fisher (1997) expressed that the average demand forecast error of a functional product was less than 10%, and for an innovative product was between 40% and 100%. This dissertation defines three levels of demand forecast error as follows: a high level of demand forecast error is where the demand forecast error is initially 100% and improves to 40% when expected demand is at its highest; a medium level of demand forecast error assumes demand forecast error is initially 100% and improves to 10% when expected demand is at its highest; and a low level of demand forecast error is where the demand forecast error is initially 40% and when expected demand is at its highest the demand forecast error improves to 10%. An illustration of the three levels of demand forecast error and expected demand with respect to time is given in Figure 6.4. Figure 6.5

illustrates $d_j \pm f_j d_j$ for the three levels of demand forecast error with respect to day j over the PLC.

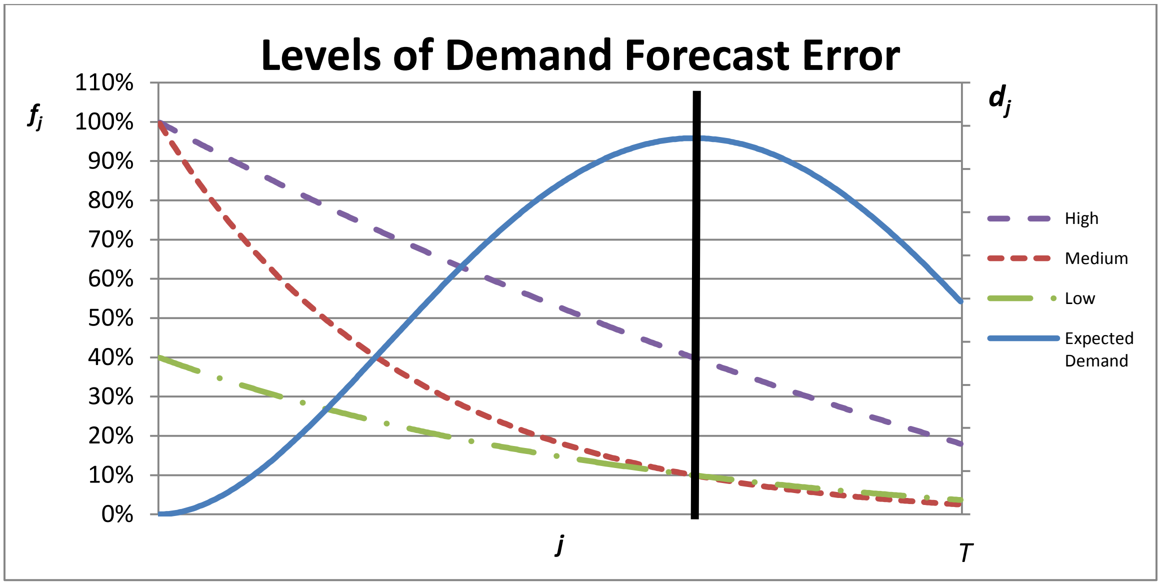


Figure 6.4: Demand forecast error and expected demand with respect to time.

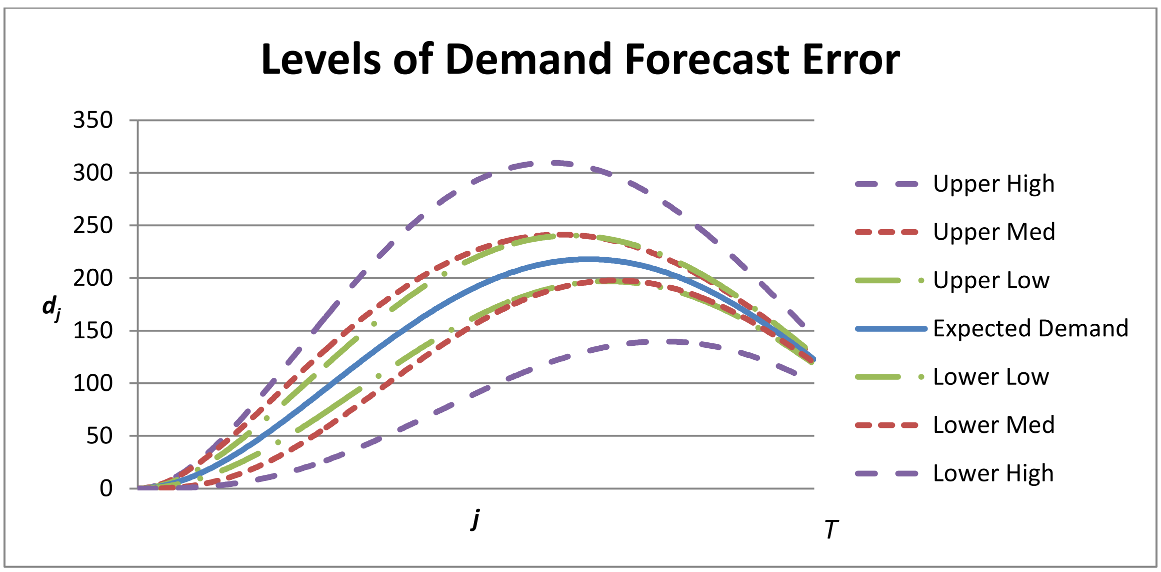


Figure 6.5: $d_j \pm f_j d_j$ for each level of demand forecast error with respect to time.

The values defined as low, medium, and high levels for *RMP*, lean index, and cost of capital are the same as in the previous chapters, and are shown in Table 6.2. The assumed values for demand forecast error are also given in Table 6.2.

Characteristics	Low	Medium	High
$RMP\ (M_L/K_L)$	1/9	1	9
Cost of Capital (i)	.01389%	.02778%	.04167%
Lean Index (β, γ)	1.01	1.02	1.04
Initial Forecast Error (f_0)	40%	100%	100%
Forecast Error at Maximum Demand $(T_F/2)$	10%	10%	40%

Table 6.2: Values for characteristics considered in Chapter 6.

The lowest PLC Total Cost for each simple SCS and the complex SCS is determined as follow: the first epoch of the PLC is enumerated for each SCS model to identify the optimal number of orders ${N_{S_1}}^*$ and ${N_{D_1}}^*$ for each SCS. This process is then repeated for each SCS and each epoch of the PLC until the values of ${N_{S_q}}^*$ and ${N_{D_q}}^*$ for all epochs of each SCS has been determined. The PLC Total Cost for each simple SCS and the complex SCS is the summation of the (discounted) Total Cost for each epoch for the PLC.

The research considers four types of simple supply chain strategies (lean, agile, leagile, and agilean). For each of the simple supply chain strategies, the SCS is constant for each epoch of the PLC. For example, with a simple lean SCS the optimal number of orders and the Total Cost of each epoch of the PLC are determined assuming a lean SCS. For the complex SCS, all four SCS types are considered for each epoch of the PLC. Therefore, for a PLC with twenty epochs, the SCS could switch many times over the PLC.

With a lean supply side strategy, for most products it seems unrealistic for a firm planning the SCS of a product over its life-cycle, which could be several years in length, to plan to place frequent (e.g., daily) orders sixty days in advance of when the expected demand will be realized. Further, in part, the cost advantage achieved by a lean SCS results from economies of scale and for many products economies of scale cannot be realized when shipping daily. For these reasons when a lean supply side strategy is considered the model limits ${N_{S_q}}^* \leq 6$. Therefore, when the supply side strategy is a lean strategy, the frequency that supply side orders can be placed is no more than approximately once every two weeks. Similarly, with a lean demand side strategy the model limits ${N_{D_q}}^* \leq 15$. Hence, with a demand side lean strategy the frequency that demand side orders can be placed is no more than once every six days or approximately once per week.

The values for supply side and demand side lead times and service levels for each simple SCS are taken from Table 3.3 and are presented in Table 6.3.

		Agile	**Agilean**	**Leagile**	**Lean**
Supply Side	Purchased Material Cost	βK_L	βK_L	K_L	K_L
	$Z_{X,S}$	$Z_{A,S}$=1.280	$Z_{A,S}$=1.280	$Z_{L,S}$=2.055	$Z_{L,S}$=2.055
	$L_{X,S}$ (days)	$L_{A,S} = 7$	$L_{A,S} = 7$	$L_{L,S} = 60$	$L_{L,S} = 60$
Demand Side	Manufacturing Cost	γM_L	M_L	γM_L	M_L
	$Z_{X,D}$	$Z_{A,D}$=1.280	$Z_{L,D}$=2.055	$Z_{A,D}$=1.280	$Z_{L,D}$=2.055
	$L_{X,D}$ (days)	$L_{A,D} = 3$	$L_{L,D} = 21$	$L_{A,D} = 3$	$L_{L,D} = 21$

Table 6.3: Time and cost variables for a lean, leagile, and agile supply chain

The PLC Total Cost function for a simple agile SCS is

$$C_{AA,3}(\tau, \delta, \psi, i) =$$

$$e^{10i} \sum_{q=1}^{Q} \left[\sum_{n_S=1}^{N_{S_q}} \left(\gamma K_L \left\{ \left(\sum_{j=j_{q(n_S-1)}+1}^{j_{qn_S}} d_j \right) + 1.280 \left(\sigma_{qn_S} - \sigma_{q(n_S-1)} \right) \right\} \right) e^{-i \left(j_{q(n_S-1)} \right)} + 200 u_{T_Q} e^{-iT_Q(q-1)} \right] +$$

$$e^{3i} \left[\sum_{n_D=1}^{N_{D_q}} \left(\gamma (100 - K_L) \left\{ \left(\sum_{j=j_{q(n_D-1)}+1}^{j_{qn_D}} d_j \right) + 1.280 \left(\sigma_{qn_D} - \sigma_{q(n_D-1)} \right) \right\} \right) e^{-i \left(j_{q(n_D-1)} \right)} + 200 v_{T_Q} e^{-iT_Q(q-1)} \right].$$

(6.34)

The PLC Total Cost function for a simple agilean SCS is

$$C_{AL,3}(\tau, \delta, \psi, i) =$$

$$e^{28i} \sum_{q=1}^{Q} \left[\sum_{n_S=1}^{N_{S_q}} \left(\gamma K_L \left\{ \left(\sum_{j=j_{q(n_S-1)}+1}^{j_{qn_S}} d_j \right) + 1.280 \left(\sigma_{qn_S} - \sigma_{q(n_S-1)} \right) \right\} \right) e^{-i \left(j_{q(n_S-1)} \right)} + 200 u_{T_Q} e^{-iT_Q(q-1)} \right] +$$

$$e^{7i} \left[\sum_{n_D=1}^{N_{D_q}} \left((100 - K_L) \left\{ \left(\sum_{j=j_{q(n_D-1)}+1}^{j_{qn_D}} d_j \right) + 2.055 \left(\sigma_{qn_D} - \sigma_{q(n_D-1)} \right) \right\} \right) e^{-i \left(j_{q(n_D-1)} \right)} + 200 v_{T_Q} e^{-iT_Q(q-1)} \right].$$

(6.35)

The PLC Total Cost function for a simple leagile SCS is

$$C_{LA,3}(\tau, \delta, \psi, i) =$$

$$e^{63i} \sum_{q=1}^{Q} \left[\sum_{n_S=1}^{N_{S_q}} \left(K_L \left\{ \left(\sum_{j=j_{q(n_S-1)}+1}^{j_{qn_S}} d_j \right) + 2.055 \left(\sigma_{qn_S} - \sigma_{q(n_S-1)} \right) \right\} \right) e^{-i \left(j_{q(n_S-1)} \right)} + 200 u_{T_Q} e^{-iT_Q(q-1)} \right] +$$

$$e^{3i} \left[\sum_{n_D=1}^{N_{D_q}} \left(\gamma (100 - K_L) \left\{ \left(\sum_{j=j_{q(n_D-1)}+1}^{j_{qn_D}} d_j \right) + 1.280 \left(\sigma_{qn_D} - \sigma_{q(n_D-1)} \right) \right\} \right) e^{-i \left(j_{q(n_D-1)} \right)} + 200 v_{T_Q} e^{-iT_Q(q-1)} \right].$$

(6.36)

The PLC Total Cost function for a simple lean SCS is

$$C_{LL,3}(\tau, \delta, \psi, i) =$$

$$e^{81i}\sum_{q=1}^{Q}\left[\sum_{n_S=1}^{N_{S_q}}\left(K_L\left\{\left(\sum_{j=j_{q(n_S-1)}+1}^{j_{qn_S}} d_j\right)+2.055\left(\sigma_{qn_S}-\sigma_{q(n_S-1)}\right)\right\}\right)e^{-i\left(j_{q(n_S-1)}\right)}+200u_{T_Q}e^{-iT_Q(q-1)}\right]+$$

$$e^{21i}\left[\sum_{n_D=1}^{N_{D_q}}\left((100-K_L)\left\{\left(\sum_{j=j_{q(n_D-1)}+1}^{j_{qn_D}} d_j\right)+2.055\left(\sigma_{qn_D}-\sigma_{q(n_D-1)}\right)\right\}\right)e^{-i\left(j_{q(n_D-1)}\right)}+200v_{T_Q}e^{-iT_Q(q-1)}\right].$$

(6.37)

${N_{S_q}}^*$ and ${N_{D_q}}^*$ for each epoch of each of each scenario presented in Figure 3.4 and the product situation combination for each SCS are found by the complete enumeration of equations (6.34), (6.35), (6.36), and (6.37). The optimal number of order periods for each epoch with respect to the SCS are used to determine the Total Cost values for $C_{AA,3}(\tau, \delta, \psi, i)$, $C_{AL,3}(\tau, \delta, \psi, i)$, $C_{LA,3}(\tau, \delta, \psi, i)$, and $C_{LL,3}(\tau, \delta, \psi, i)$ when expected demand mimics the classical PLC and demand forecast error improves with time. Figures 6.6-6.11 shows the simple SCS that results in the lowest PLC Total Cost for each of the scenarios presented in Table 6.1 for the six situations considered ($D_T=$100,000 or 1,000,000 units, and $T=$1 year, 2 years, or 5 years). Out of the 486 scenarios considered (81*6) there are only three instances (0.6%) where the complex SCS resulted in a lower PLC Total Cost than a simple SCS. These three cases all occur when the PLC length is 5 years and the total expected demand is 100,000 units. The cases where the complex SCS results in a lower PLC Total Cost are noted in Figure 6.6 by the cells shaded with diagonal lines. The legend for Figures 6.6-6.11 is shown with Figure 6.6.

5 years 100,000 units				Demand Forecast Error								
				Low			Medium			High		
				Cost of Capital			Cost of Capital			Cost of Capital		
				Low	Med	High	Low	Med	High	Low	Med	High
Lean Index	High	*RMP*	High	LL	LL	LL	LL	LL	LL	LL	LL	LL
			Med	LL	LL	LL	LL	LL	LL	LL	LL	LL
			Low	LL	LA	LA	LL	LA	LA	LL	LA	LA
	Med	*RMP*	High	LL	LL	AL	LL	LL	AL	LL	LL	AL
			Med	LL	LL	AL	LL	LL	AL	LL	LL	LL
			Low	LA	LA	AA	LA	LA	AA	LA	LA	LA
	Low	*RMP*	High	AL	AL	AL	AL	AL	AL	LL	AL	AL
			Med	LL	AA	AA	AA	AA	AA	LL	AA	AA
			Low	LA	AA	AA	LA	AA	AA	LA	AA	AA

Lean SCS LL	Agile SCS AA	Leagile SCS LA	Agilean SCS AL

Figure 6.6: The simple SCS that results in the lowest PLC Total Cost when D_T=100,000 and T =5 years for each scenario.

5 years. 1,000,000 units				Demand Forecast Error								
				Low			Medium			High		
				Cost of Capital			Cost of Capital			Cost of Capital		
				Low	Med	High	Low	Med	High	Low	Med	High
Lean Index	High	*RMP*	High	LL	LL	LL	LL	LL	LL	LL	LL	LL
			Med	LL	LL	LL	LL	LL	LL	LL	LL	LL
			Low	LL	LA	LA	LL	LA	LA	LL	LA	LA
	Med	*RMP*	High	LL	LL	AL	LL	LL	AL	LL	LL	LL
			Med	LL	LL	AL	LL	LL	AL	LL	LL	AL
			Low	LA	LA	AA	LA	LA	AA	LA	LA	AA
	Low	*RMP*	High	LL	AL	AL	LL	AL	AA	LL	AL	AL
			Med	LL	AL	AA	LL	AL	AA	LL	AL	AA
			Low	LA	AA	AA	LA	AA	AA	LA	AA	AA

Figure 6.7: The simple SCS that results in the lowest PLC Total Cost when D_T=1,000,000 and T =5 years for each scenario.

2 years 100,000 units		Demand Forecast Error: Low			Demand Forecast Error: Medium			Demand Forecast Error: High		
		Cost of Capital			Cost of Capital			Cost of Capital		
Lean Index	RMP	Low	Med	High	Low	Med	High	Low	Med	High
High	High	LL	LL	LL	LL	LL	LL	LL	LL	LL
High	Med	LL	LL	LL	LL	LL	LL	LL	LL	LL
High	Low	LL	LA	LA	LL	LA	LA	LL	LA	LA
Med	High	LL	LL	AL	LL	LL	AL	LL	LL	LL
Med	Med	LL	LL	AL	LL	LL	AL	LL	LL	AL
Med	Low	LA	LA	AA	LA	LA	AA	LA	LA	AA
Low	High	LL	AL	AL	LL	AL	AL	LL	AL	AL
Low	Med	LL	AA	AA	LL	AA	AA	LL	AL	AA
Low	Low	LA	AA	AA	LA	AA	AA	LA	AA	AA

Figure 6.8: The simple SCS that results in the lowest PLC Total Cost when D_T=100,000 and T =2 years for each scenario.

2 years 1,000,000 units		Demand Forecast Error: Low			Demand Forecast Error: Medium			Demand Forecast Error: High		
		Cost of Capital			Cost of Capital			Cost of Capital		
Lean Index	RMP	Low	Med	High	Low	Med	High	Low	Med	High
High	High	LL	LL	LL	LL	LL	LL	LL	LL	LL
High	Med	LL	LL	LL	LL	LL	LL	LL	LL	LL
High	Low	LL	LA	LA	LL	LA	LA	LL	LA	LA
Med	High	LL	LL	AL	LL	LL	AL	LL	LL	AL
Med	Med	LL	LL	AL	LL	LL	AL	LL	LL	AL
Med	Low	LA	LA	AA	LA	LA	AA	LA	LA	AA
Low	High	LL	AL	AL	LL	AL	AL	LL	AL	AA
Low	Med	LL	AL	AA	LL	AL	AA	LL	AA	AA
Low	Low	LA	AA	AA	LA	AA	AA	LA	AA	AA

Figure 6.9: The simple SCS that results in the lowest PLC Total Cost when D_T=1,000,000 and T =2 years for each scenario.

1 year 100,000 units

Lean Index		RMP	Demand Forecast Error: Low Cost of Capital: Low	Low Med	Low High	Medium Low	Medium Med	Medium High	High Low	High Med	High High
Lean Index	High	*RMP* High	LL	LL	LL	LL	LL	LL	LL	LL	LL
	High	*RMP* Med	LL	LL	LL	LL	LL	LL	LL	LL	LL
	High	*RMP* Low	LL	LA	LA	LL	LA	LA	LL	LA	LA
	Med	*RMP* High	LL	LL	AL	LL	LL	AL	LL	LL	AL
	Med	*RMP* Med	LL	LL	AL	LL	LL	AL	LL	LL	AL
	Med	*RMP* Low	LA	LA	AA	LA	LA	AA	LA	LA	AA
	Low	*RMP* High	LL	AL	AL	LL	AL	AL	LL	AL	AL
	Low	*RMP* Med	LL	AL	AA	LL	AL	AA	LL	AL	AA
	Low	*RMP* Low	LA	AA	AA	LA	AA	AA	LA	AA	AA

Figure 6.10: The simple SCS that results in the lowest PLC Total Cost when D_T=100,000 and T =1 year for each scenario.

1 year 1,000,000 units

Lean Index		RMP	Demand Forecast Error: Low Cost of Capital: Low	Low Med	Low High	Medium Low	Medium Med	Medium High	High Low	High Med	High High
Lean Index	High	*RMP* High	LL	LL	LL	LL	LL	LL	LL	LL	LL
	High	*RMP* Med	LL	LL	LL	LL	LL	LL	LL	LL	LL
	High	*RMP* Low	LL	LA	LA	LL	LA	LA	LL	LA	LA
	Med	*RMP* High	LL	LL	AL	LL	LL	AL	LL	LL	AL
	Med	*RMP* Med	LL	LL	AL	LL	LL	AL	LL	AL	AL
	Med	*RMP* Low	LA	LA	AA	LA	LA	AA	LA	AA	AA
	Low	*RMP* High	LL	AL	AL	LL	AL	AL	LL	AL	AA
	Low	*RMP* Med	LL	AA	AA	LL	AA	AA	AL	AA	AA
	Low	*RMP* Low	LA	AA	AA	LA	AA	AA	AA	AA	AA

Figure 6.11: The simple SCS that results in the lowest PLC Total Cost when D_T=1,000,000 and T =1 year for each scenario.

Some observations from Figures 6.6-6.11 follow. With a high lean index the simple SCS that results in the lowest PLC Total Cost is independent of both the length of the PLC and the level of total expected demand considered (i.e. the top 3 rows of Figures

6.6-6.11 are the same). Further, when the lean index is medium and the demand forecast error is either low or medium, the simple SCS that results in the lowest PLC Total Cost is independent of both the length of the PLC and level of total expected demand considered.

From Figures 6.6 and 6.7 for a 5 year PLC, with a low lean index there are seven of twenty-seven scenarios where the simple SCS that results in the lowest PLC Total Cost differs as the total expected demand is increased from 100,000 to 1 million, and in six of those instances the simple SCS changes to a leaner SCS. The one scenario where the lowest cost SCS become more agile is with low lean index, high *RMP*, medium demand forecast error, and high cost of capital. Also from Figures 6.6 and 6.7 for a 5 year PLC, when the lean index is medium there are three instances where the SCS changes as the total expected demand is increased from 100,000 to 1 million units, and in all three instances the cost of capital and demand forecast error are high. When *RMP* is either medium or low the SCS becomes more agile and when *RMP* is high the SCS becomes leaner. In contrast, when the PLC was one year in length, as shown in Figures 6.10 and 6.11, all eight scenarios where the simple SCS that gives the lowest PLC Total Cost differs when total expected demand is increased from 100,000 to 1,000,000 units moves towards a more agile SCS. Six of the instances are with a low index and six are with high demand forecast error.

From Figures 6.6, 6.8, and 6.10, when total expected demand is 100,000 and the length of the PLC is decreased from five years to one year and both demand forecast error and cost of capital are not at a high level, there are six instances where the simple SCS differs and in all six cases the SCS moves to a leaner SCS. When both demand forecast error and cost of capital are high and the SCS that results in the lowest Total

Cost differs as the length of the PLC decreases, in the majority of instances the SCS moves towards a more agile SCS.

When Figures 6.7, 6.9, and 6.11 are examined, in nine of the ten instances where the simple SCS differs as the length of the PLC is shortened, the simple SCS that results in the lowest PLC Total Cost moves towards a more agile SCS. The single instance where this is not the case occurs with low lean index, high *RMP*, medium demand forecast error, high cost of capital, and the length of the PLC is shortened from 5 years to 2 years; where the simple SCS that results in the lowest PLC Total Cost changes from a simple agile SCS to a simple agilean SCS.

In summary, based on the parameters considered, all instances where the SCS differs because either the total expected demand or the length of the PLC is changed occur when either the lean index level is low or when the lean index level is medium and demand forecast error is at a high level. Under these scenarios the following changes in simple supply chain strategies are observed. First, when total expected demand is 100,000 units and the length of the PLC is increased, a more agile SCS may reduce the PLC Total Cost of a product. Second, in contrast to the first observation, when total expected demand is one million units and the length of the PLC is increased, then a leaner SCS may reduce the PLC Total Cost of a product. Third, when the length of the PLC is 5 years and the total expected demand is increased, then a leaner SCS may reduce the PLC Total Cost of a product. Last, conversely to the third observation, when the length of the PLC is one year and total expected demand is increased, then a more agile SCS may reduce the PLC Total Cost of a product. This suggests that the simple SCS that results in the lowest PLC Total Cost for a product where the lean index level is low or when the lean index level is medium and the high demand forecast error is dependent on both the length of the PLC and total expected demand of the product. Note that for the majority of scenarios considered, 396 out of 486 (81%), the simple SCS that results in the lowest PLC Total Cost is independent of both the lengths of the PLC and the total expected demand levels considered.

From Figure 6.6, the scenarios where the complex SCS results in a lower PLC Total Cost than any simple SCS occurs when the PLC is 5 years, total expected demand is 100,000 units, low *RMP*, high lean index, and low demand forecast error. In all three of these scenarios, a simple SCS results in a lower PLC Total Cost than the complex SCS when total expected demand is increased to one million units. Table 6.4 gives the percent difference between the PLC Total Cost of the complex SCS and the simple SCS that results in the lowest PLC Total Cost. In all three cases the NPV cost advantage of the complex SCS is very small (<0.1%) compared to the best simple SCS. The Total Cost difference between the best simple SCS and the complex SCS is also presented in Table 6.4, with the largest difference being just under $6,100 over 5 years.

Cost of Capital (Annually)	Low (5%)	Medium (10%)	High (15%)
Percent Difference	0.018%	0.080%	0.007%
Total Cost Difference	$1,560	$6,073	$438

Table 6.4: Percent difference in the PLC Total Cost of the complex SCS and the best simple SCS

To determine the approximate total expected demand that minimizes the difference between the PLC Total Cost of the complex SCS and the simple SCS with the lowest PLC Total Cost, the model is evaluated for total expected demand values from 100,000 to 1 million in increments of 100,000. The PLC Total Cost of the complex SCS and a simple lean SCS are approximately equal when the total expected demand is 700,000 units and the cost of capital is 5% annually (low level). When the cost of capital is increased to a medium level (10% annually), the PLC Total Cost of a complex SCS and a simple leagile SCS are approximately equal when the total expected demand is 400,000 units. The PLC Total Cost of the complex SCS and a simple leagile SCS are nearly equal when the total expected demand is slightly more than 100,000 units and the cost of capital is at a high level (15% annually).

6.3 Examples

This section presents detailed results associated with three scenarios corresponding to: (i) a functional product, (ii) a hybrid product, and (iii) an innovative product. The functional product has a long PLC (5 years) and the demand forecast error and the cost of capital are at a low level. The hybrid product has a medium length PLC (2 years), medium demand forecast error, and medium cost of capital. The innovative product has a short PLC (1 year), high demand forecast error, and high cost of capital. To focus the discussion on the impact of product type, the *RMP* value for all three scenarios examined is set at a medium level as defined in Table 6.1.

6.3.1 Functional product

Fisher (1997) described a functional product in part as a product that has a long PLC of 2 or more years and a demand forecast error of less than 10%. This research uses the following scenario for a functional product: (i) a PLC of 5 years and the total expected demand for the PLC of one million units, and (ii) low demand forecast error, low cost of capital, medium *RMP*, and high lean index, all as defined in Table 6.1.

Epoch	Lean SCS	Agile SCS	Leagile SCS	Agilean SCS	Complex SCS	Complex SCS	Expected Demand
1	$65	$64	$64	$64	$64	Agile	556
2	$377	$382	$381	$378	$379	Lean	3,637
3	$914	$935	$926	$923	$914	Lean	9,130
4	$1,600	$1,644	$1,625	$1,620	$1,600	Lean	16,362
5	$2,375	$2,449	$2,415	$2,409	$2,375	Lean	24,716
6	$3,182	$3,284	$3,236	$3,230	$3,182	Lean	33,636
7	$3,974	$4,110	$4,045	$4,039	$3,974	Lean	42,626
8	$4,712	$4,875	$4,797	$4,790	$4,712	Lean	51,249
9	$5,364	$5,551	$5,461	$5,454	$5,364	Lean	59,128
10	$5,904	$6,112	$6,011	$6,005	$5,904	Lean	65,946
11	$6,314	$6,537	$6,429	$6,423	$6,314	Lean	71,444
12	$6,581	$6,814	$6,701	$6,695	$6,581	Lean	75,424
13	$6,698	$6,936	$6,820	$6,814	$6,698	Lean	77,747
14	$6,664	$6,901	$6,786	$6,780	$6,664	Lean	78,333
15	$6,482	$6,709	$6,599	$6,593	$6,482	Lean	77,163
16	$6,162	$6,378	$6,273	$6,268	$6,162	Lean	74,276
17	$5,716	$5,918	$5,819	$5,815	$5,716	Lean	69,772
18	$5,163	$5,345	$5,256	$5,252	$5,163	Lean	63,809
19	$4,524	$4,681	$4,604	$4,601	$4,524	Lean	56,605
20	$3,824	$3,957	$3,892	$3,889	$3,824	Lean	48,440
Total Cost	$86,594	$89,584	$88,141	$88,041	$86,595		
Total Cost Difference	$0	$2,989	$1,546	$1,447	$1		
Pct. Difference	0.00%	3.45%	1.79%	1.67%	0.00%		

Table 6.5: Functional product scenario cost ($,000) information for each simple SCS and the complex SCS by epoch.

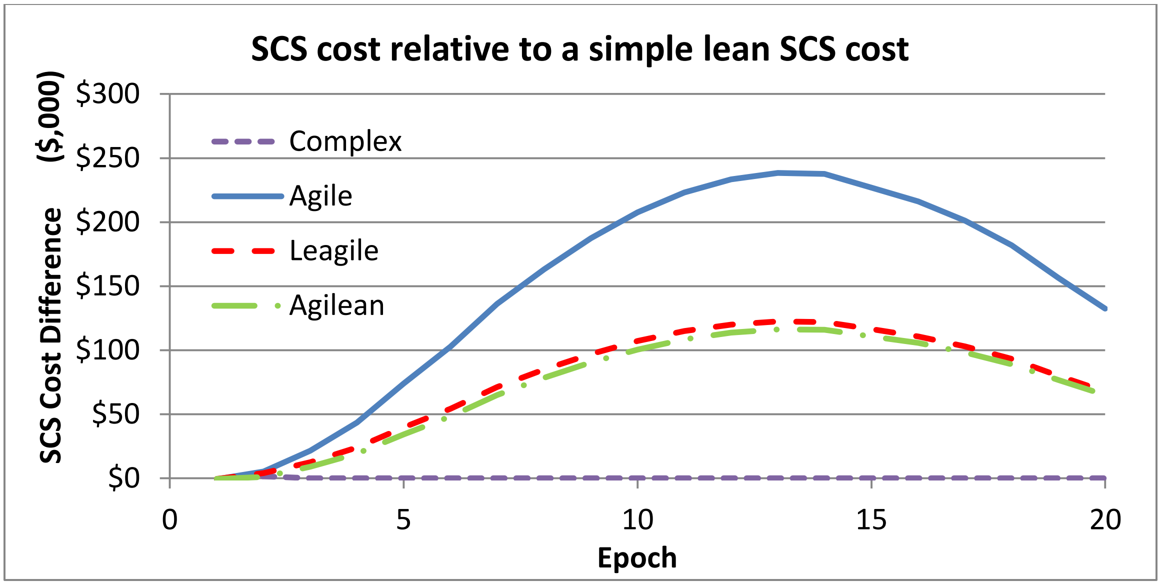


Figure 6.12: Each SCS cost per epoch relative to the simple lean SCS for the functional product scenario.

The length of each epoch of the PLC is assumed to be 90 days; therefore, a 5 year PLC is subdivided into twenty epochs, as illustrated in Table 6.5 and Figures 6.12-6.14. Table 6.5 shows the Total Cost of each simple SCS (columns 2-5) and the complex SCS (column 6) per epoch, plus the relative and percentage cost difference of each SCS to the SCS with the lowest PLC Total Cost. The complex SCS uses an agile SCS in the first epoch and a lean SCS in all other epochs. The PLC Total Cost difference between a simple lean SCS and the complex SCS is less than a $1,000 over five years. Table 6.5 also shows that choosing an inappropriate simple SCS can result in a considerable Total Cost impact over the PLC. A simple agile SCS will cost approximately $3 million more than a simple lean SCS and a simple leagile SCS or a simple agilean SCS will cost approximately $1.5 million more than a simple lean SCS. Figure 6.12 illustrates the cost difference of each SCS relative to the lowest PLC Total Cost SCS (simple lean SCS) for each epoch. From Figure 6.12, early in the PLC when expected demand is low, the relative cost difference between each simple supply chain strategy and the lowest PLC

Total Cost SCS is small. However, as the expected demand per epoch increases the cost impact of adopting a less effective SCS becomes significant, and may exceed $230 thousand an epoch for a simple agile SCS.

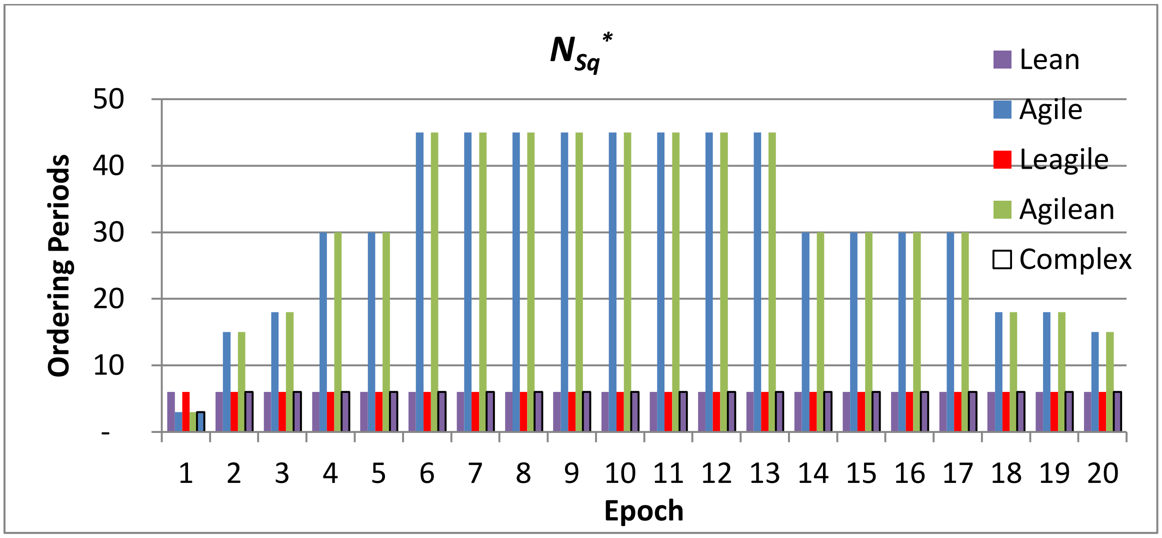


Figure 6.13: Functional product scenario $N_{S_q}{}^*$ per epoch for each SCS.

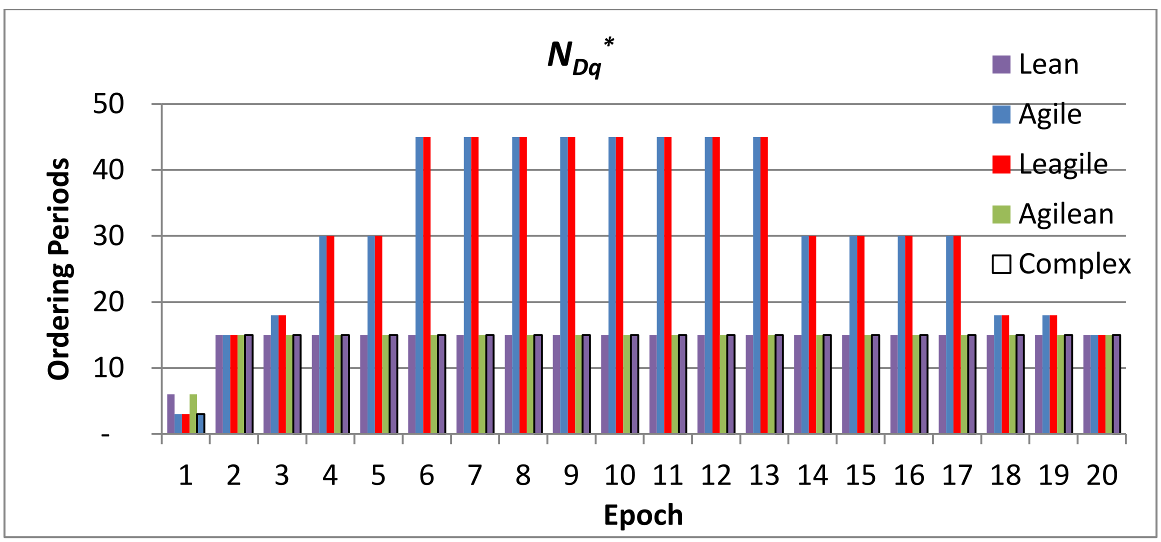


Figure 6.14: Functional product scenario $N_{D_q}{}^*$ per epoch for each SCS.

Figure 6.13 shows the optimal number of supply side ordering periods, $N_{S_q}{}^*$, and Figure 6.14 shows the optimal number of demand side ordering periods, $N_{D_q}{}^*$, for each epoch of the various supply chain strategies. In Figure 6.13 and Figure 6.14 the bars showing the number of ordering periods for the complex SCS are shaded with the color of the SCS for that epoch of the PLC. Note for the supply side, the number of ordering periods for the simple lean and the simple leagile supply chain strategies and the number of ordering periods per epoch for the simple agile and the simple agilean supply chain strategies are the same for each epoch of the PLC, because the pairs of supply chain strategies share the same supply side strategy. Similarly, for the demand side the number of ordering periods for the simple lean SCS and the simple agilean SCS are equal, and the number of ordering periods per epoch for the simple agile SCS and the simple agilean SCS are the same for each epoch of the PLC, because the pairs of supply chain strategies share the same demand side strategy.

From Figure 6.13, the optimal number of orders when a lean strategy is considered for the supply side is constrained by the frequency that orders could be made (6 orders per epoch). From Figure 6.13, on the supply side with the lean strategy there were three orders for the first epoch and six orders for each of the remaining epochs. From Figure 6.14, the optimal number of orders when a lean strategy is considered for the demand side is constrained by the frequency that orders could be made (15 orders per epoch), with three orders for the first epoch and fifteen orders for each of the remaining epochs. The optimal number of orders for an agile strategy was limited to one order per day or 90 orders per epoch. With the agile strategy the optimal number of orders increased steadily on both sides of the supply chain as the expected demand increased, then stabilized at 45 orders per epoch; as total expected demand per epoch decreased the optimal number orders per epoch decreased.

6.3.2 Hybrid product

A number of researchers have found that some products exhibit characteristics of both a functional product and an innovative product (Lee, 2002; Ernst and Kamrad, 2000; Li and O'Brien, 2001; Christopher and Towill, 2002; Huang et al. 2002; Cigolini et al., 2004; Wong et al., 2006; and Lo and Power, 2010). This research uses the following scenario for a hybrid product: (i) a PLC of 2 years with a total expected demand over the PLC of one hundred thousand units, medium demand forecast error, medium cost of capital, medium *RMP*, and medium lean index, all as defined in Table 6.1.

Epoch	Lean SCS	Agile SCS	Leagile SCS	Agilean SCS	Complex SCS	Complex SCS	Expected Demand
1	$98	$93	$96	$95	$93	Agile	795
2	$476	$469	$474	$470	$469	Agile	4,645
3	$971	$977	$975	$972	$977	Agile	10,085
4	$1,411	$1,425	$1,419	$1,417	$1,423	Agilean	15,174
5	$1,679	$1,698	$1,689	$1,688	$1,688	Agilean	18,556
6	$1,718	$1,736	$1,728	$1,726	$1,726	Agilean	19,455
7	$1,524	$1,539	$1,532	$1,531	$1,529	Lean	17,678
8	$1,146	$1,156	$1,152	$1,151	$1,146	Lean	13,612
Total Cost	$9,023	$9,093	$9,066	$9,051	$9,051		
Total Cost Difference	$0	$70	$43	$28	$28		
Pct. Difference	0.00%	0.78%	0.47%	0.31%	0.32%		

Table 6.6: Hybrid product scenario cost ($,000) information for each simple SCS and the complex SCS by epoch.

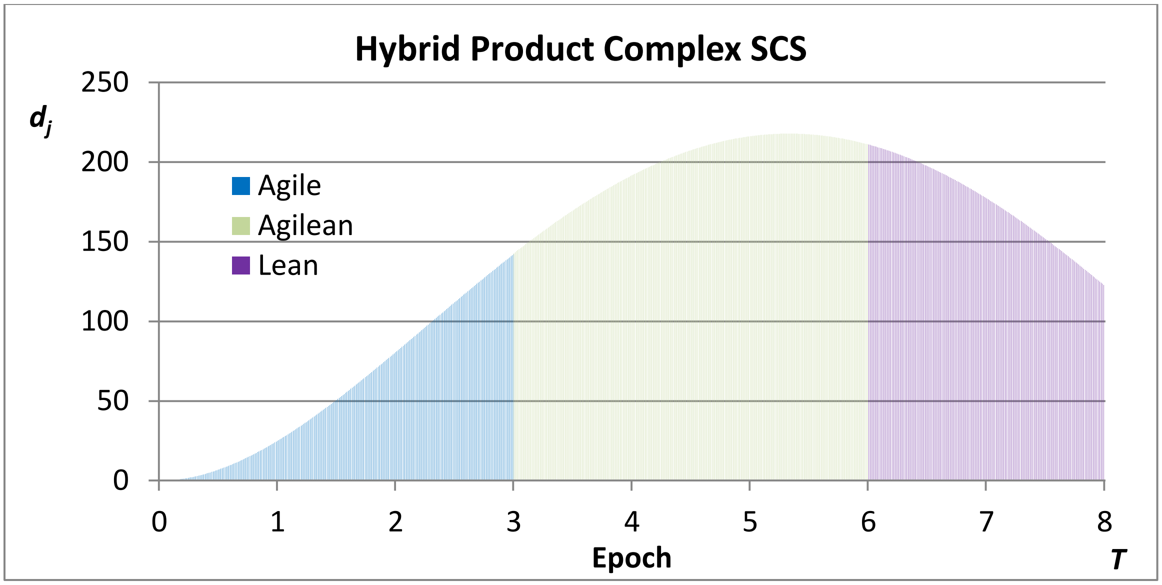


Figure 6.15: Supply chain strategies of the complex SCS for the hybrid product scenario.

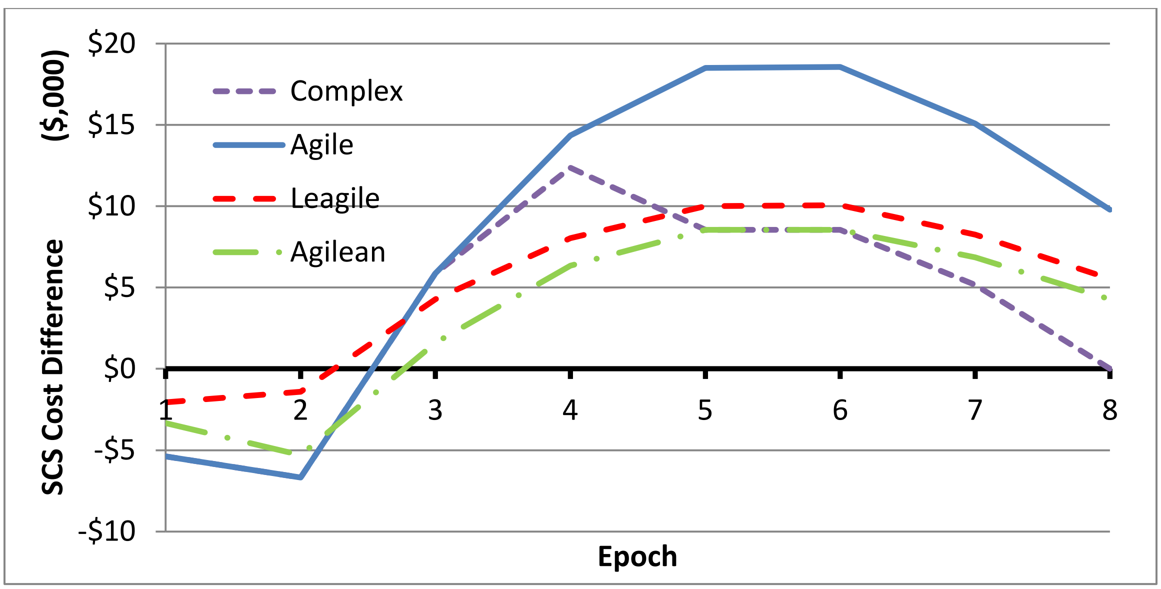


Figure 6.16: Each SCS cost per epoch relative to the simple lean SCS for the hybrid product scenario.

Table 6.6 shows that a simple lean SCS results in a slightly lower PLC Total Cost than a simple agilean SCS or a complex SCS. The complex SCS is a combination of three supply chain strategies, an agile SCS for the first three epochs, then an agilean SCS for the next three epochs and a lean SCS for the last two epochs, shown in Figure 6.15. The combination of supply chain strategies shown in Table 6.6 and Figure 6.15 is similar to the scheme presented in Figure 1.3, where an agile SCS is employed in the introduction stage of the PLC, changes to a compound SCS (leagile or agilean SCS), and finally ends the PLC with a lean SCS. As seen in Figures 6.6-6.11, the compound simple supply chain strategies (leagile SCS and agilean SCS) are more likely to result in the lowest PLC Total Cost when *RMP* is either high (simple agilean SCS) or low (simple leagile SCS).

If the supply chain elects to continue to use the SCS that results the lowest Total Cost for the first epoch, a simple agile SCS, then the NPV cost to the supply chain would be approximately $70,000 (0.8%) more than the minimal cost SCS over the PLC, and the agile SCS is the least effective SCS for minimizing the Total Cost over the PLC for this scenario. Figure 6.16 and Table 6.6 show that the NPV cost of a complex SCS is lower than that of the simple lean SCS for the first two epochs, but from the third to the seventh epoch the simple lean SCS provided a lower NPV cost per epoch than the complex SCS. The NPV cost of the simple lean SCS and the complex SCS are equal for the eighth epoch of the PLC.

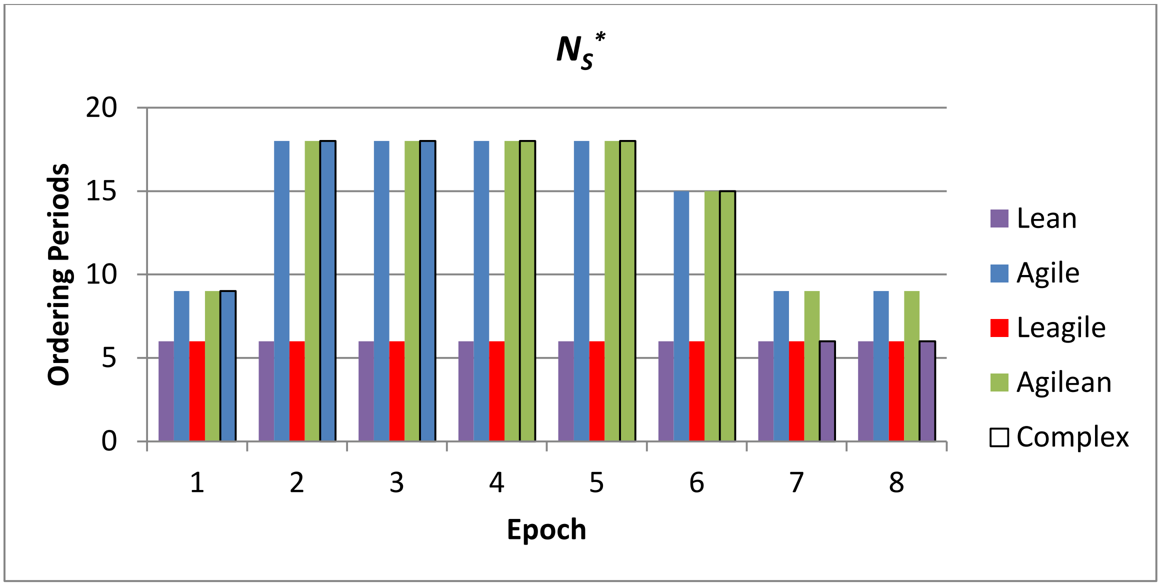


Figure 6.17: Hybrid product scenario $N_{S_q}{}^*$ per epoch for each SCS

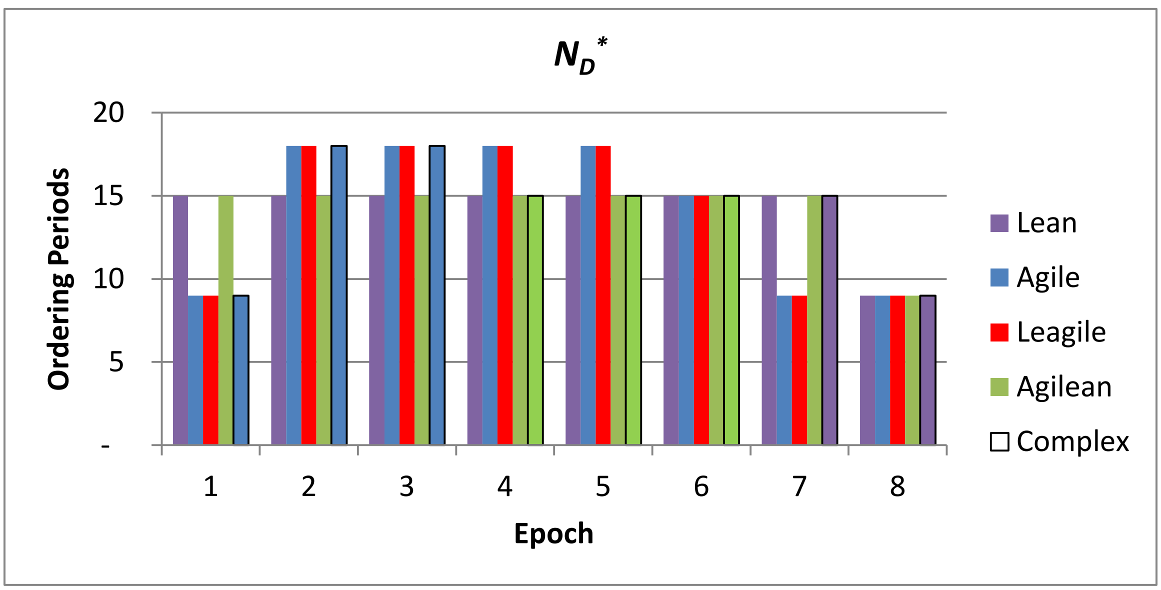


Figure 6.18: Hybrid product scenario $N_{D_q}{}^*$ per epoch for each SCS.

Figure 6.17 shows the optimal number of supply side ordering periods, $N_{S_q}{}^*$, and Figure 6.18 shows the optimal number of demand side ordering periods, $N_{D_q}{}^*$, for each epoch of the various supply chain strategies for the hybrid product scenario. In Figure 6.17 and Figure 6.18 the bars showing the number of ordering periods for the complex

SCS are shaded with the color of the SCS of the complex SCS for that epoch of the PLC. From Figure 6.17, the optimal number of orders when a lean strategy is used for the supply side is always six, which reflects the constraint on the frequency that orders can be made. On the demand supply side, Figure 6.18, with the lean strategy there are fifteen orders in every epoch, except the last epoch, which uses nine orders. The optimal number of orders for an agile strategy is limited to one per day or 90 orders per epoch. With the agile strategy the optimal number of orders increases quickly to 18 orders per epoch starting with the second epoch for both sides of the supply chain, and as total expected demand per epoch decreases the optimal number orders per epoch decreases.

6.3.3 Innovative product

Fisher (1997) described an innovative product in part as a product that has a PLC of 1 year or less and a demand forecast error greater than 40%. This research uses the following scenario for an innovative product: (i) a PLC of one year with a total expected demand for the PLC of one hundred thousand units, and (ii) high demand forecast error, high cost of capital, medium *RMP*, and low lean index, all as defined in Table 6.1.

Epoch	Lean SCS	Agile SCS	Leagile SCS	Agilean SCS	Complex SCS	Complex SCS	Expected Demand
1	$653	$586	$630	$608	$586	Agile	5,440
2	$2,527	$2,452	$2,505	$2,473	$2,452	Agile	25,259
3	$3,501	$3,508	$3,507	$3,501	$3,508	Agile	38,011
4	$2,731	$2,775	$2,748	$2,758	$2,775	Agile	31,290
Total Cost	$9,412	$9,320	$9,391	$9,341	$9,320		
Total Cost Difference	$92	$0	$71	$20	$0		
Pct. Difference	0.98%	0.00%	0.76%	0.22%	0.00%		

Table 6.7: Innovative product scenario cost ($,000) information for each simple SCS and the complex SCS by epoch.

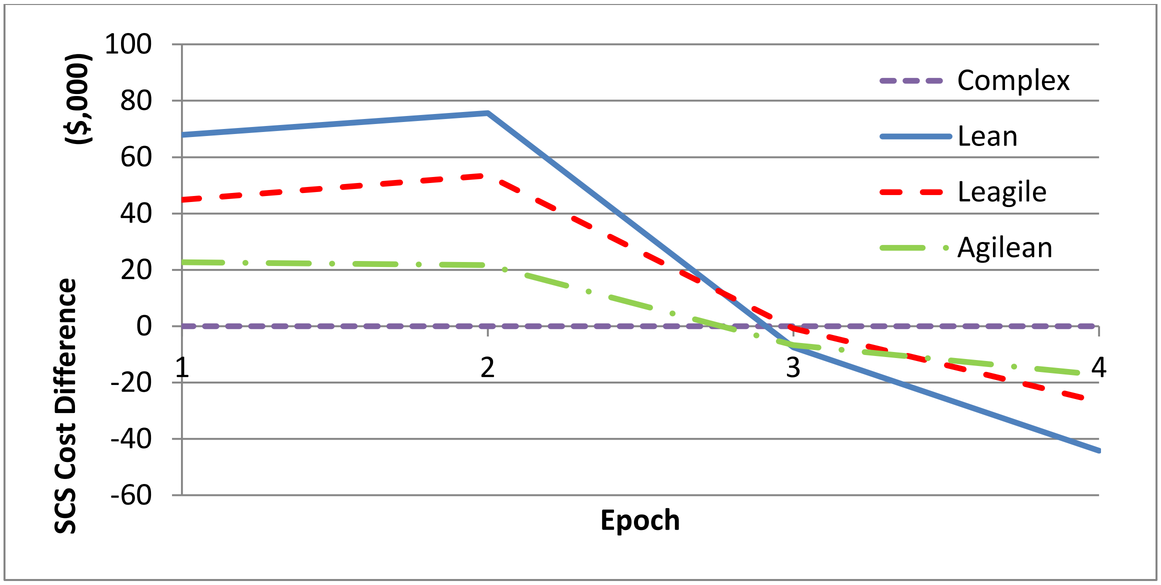


Figure 6.19: Each SCS cost per epoch relative to the simple agile SCS for the innovative product scenario.

Table 6.7 shows that the simple agile SCS and the complex SCS are the same, and thus result in the same PLC Total Cost. For this scenario the flexibility of the complex SCS to change strategies is not exploited: the lowest cost strategy is to use an agile SCS in every epoch. Table 6.7 and Figure 6.19 show that for the third epoch of the PLC the Total Costs for all the supply chain strategies considered are approximately equal and the simple lean SCS results in the lowest Total Cost of the fourth epoch. Table 6.7 shows that the worst of the supply chain strategies considered when the objective is NPV cost minimization for an innovative product is a simple lean SCS, which is nearly 1% more expensive than the simple agile SCS.

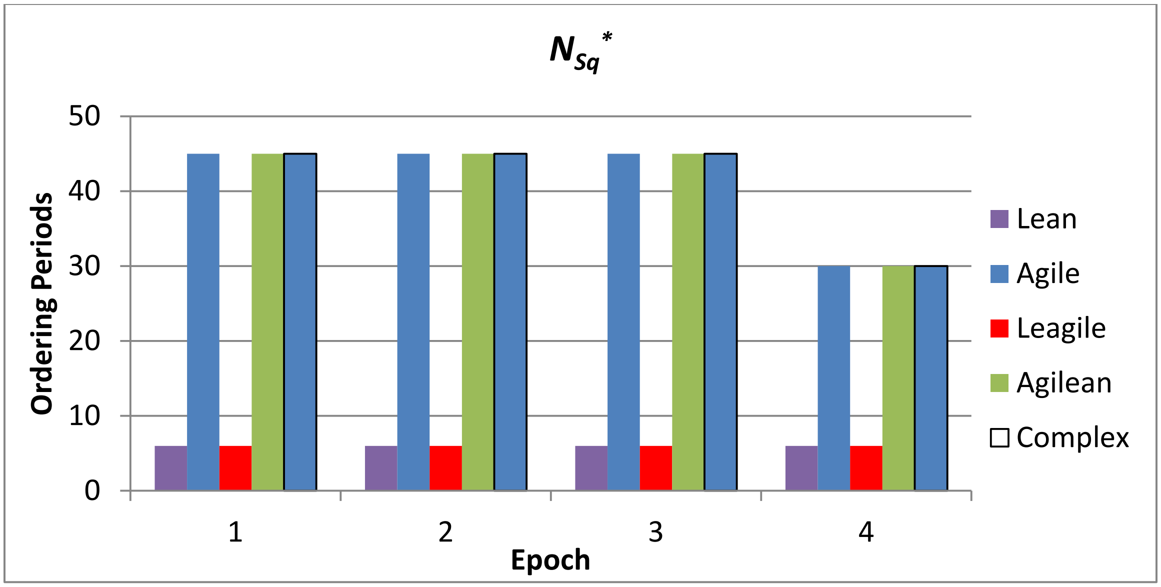


Figure 6.20: Innovative product scenario $N_{S_q}{}^*$ per epoch for each SCS

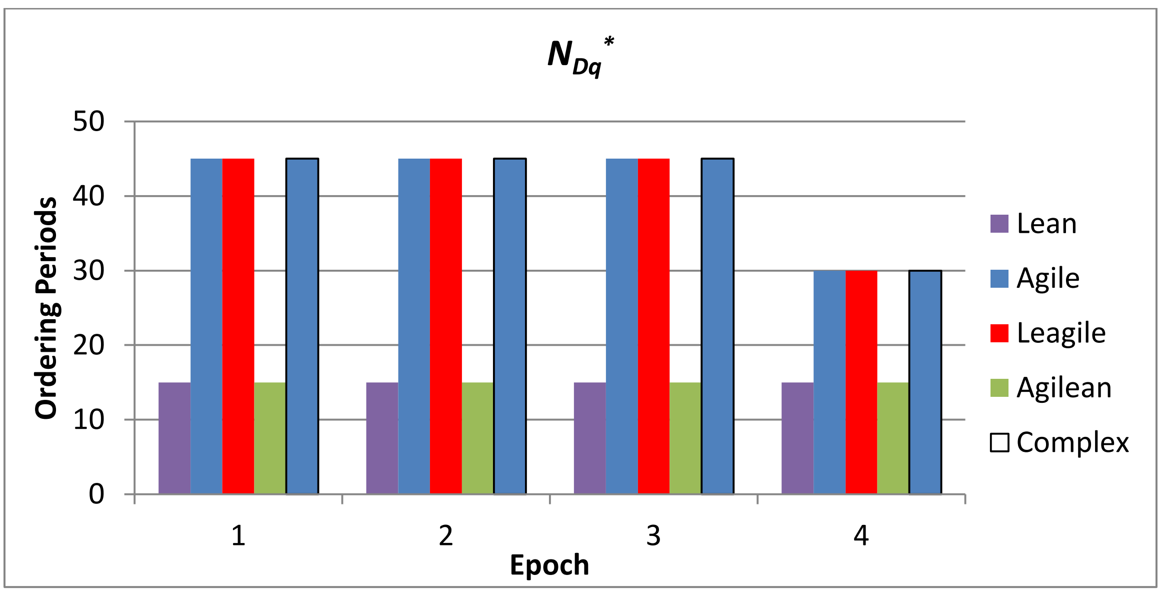


Figure 6.21: Innovative product scenario $N_{D_q}{}^*$ per epoch for each SCS.

Figure 6.20 shows the number of supply side ordering periods, $N_{S_q}{}^*$, and Figure 6.21 shows the number of demand side ordering periods, $N_{D_q}{}^*$, for each epoch of the various supply chain strategies for the innovative product scenario. In Figure 6.20 and Figure 6.21 the columns showing the number of ordering periods for the complex SCS are shaded with the color of the SCS of the complex SCS for that epoch of the PLC. From Figure 6.20 and 6.21, the optimal number of orders when a lean strategy is used for both the supply side and the demand side appears to be constrained by the frequency at which orders can be made. For both the supply side and the demand side when a lean strategy is considered, the maximum allowable number of orders per epoch is employed for all epochs. The optimal number of orders for an agile strategy is limited to 90 orders per epoch. With the agile strategy the optimal number of orders per epoch started at 45 orders for both sides of the supply chain and only decreases during the fourth epoch as total expected demand per epoch decreases.

Considering the three scenarios presented in this section the following statements can be made. (i) For the functional and innovative product, adopting the complex SCS results in a PLC Total Cost that is almost as low as or the same as the best simple SCS. (ii) The worst product type to adopt a complex SCS for is the hybrid product. (iii) Adopting the wrong strategy can have a significant cost impact, and this impact is the greatest when a wrong strategy is adopted for a functional product.

6.4 Agile SCS to a lean SCS

In Figure 1.3, a scenario is presented where the SCS of a product evolves over the life-cycle: starting with an agile SCS, then evolving to a compound SCS (leagile or agilean), and then evolving again to a lean SCS. Although the research findings demonstrates for the majority of scenarios considered that a supply chain should adopt a single SCS to minimize PLC Total Cost, this section examines the question of how the SCS should evolve for those supply chains that plan to evolve the SCS as the product progresses through its PLC. As the supply chain goes from an agile SCS to a compound

SCS, which side (demand or supply) of the supply chain should evolve first? Evolving the supply side first means the supply chain will evolve to a leagile SCS, and evolving the demand side first means the supply chain will evolve to an agilean SCS. From this research it is observed that when evolving the SCS over the PLC the lowest cost SCS is more sensitive to the *RMP* of the supply chain. Three scenarios are considered with *RMP* at a different level for each scenario and the other characteristics of the scenarios are constant: medium lean index, low cost of capital, and medium demand forecast error. The length of the PLC for each scenario was 2 years and D_T was one million units. The three scenarios are of a hybrid product type; however, this analysis is independent of the product type and would apply to a functional product employing an agile SCS and is evolving the SCS to a lean SCS.

6.4.1 High *RMP*

The first scenario considered is with high *RMP*. The costs per epoch for each simple SCS and the complex SCS, as well as the strategy of the complex SCS per epoch are presented in Table 6.8.

Epoch	Lean SCS	Agile SCS	Leagile SCS	Agilean SCS	Complex SCS	Complex SCS	Expected Demand
1	$918	$860	$868	$911	$860	Agile	7,947
2	$4,723	$4,707	$4,715	$4,716	$4,707	Agile	46,453
3	$9,858	$10,004	$9,993	$9,869	$10,004	Agilean	100,846
4	$14,548	$14,832	$14,807	$14,574	$14,768	Agilean	151,739
5	$17,545	$17,904	$17,871	$17,578	$17,574	Lean	185,559
6	$18,171	$18,541	$18,507	$18,205	$18,171	Lean	194,553
7	$16,318	$16,640	$16,613	$16,346	$16,318	Lean	176,781
8	$12,420	$12,653	$12,633	$12,440	$12,420	Lean	136,121
Total Cost	$94,503	$96,142	$96,008	$94,638	$94,824		
Total Cost Difference	$0	$1,638	$1,505	$134	$321		
Pct. Difference	0.00%	1.45%	0.74%	0.71%	0.30%		

Table 6.8: High *RMP* scenario cost ($,000) information for each simple SCS and the complex SCS by epoch.

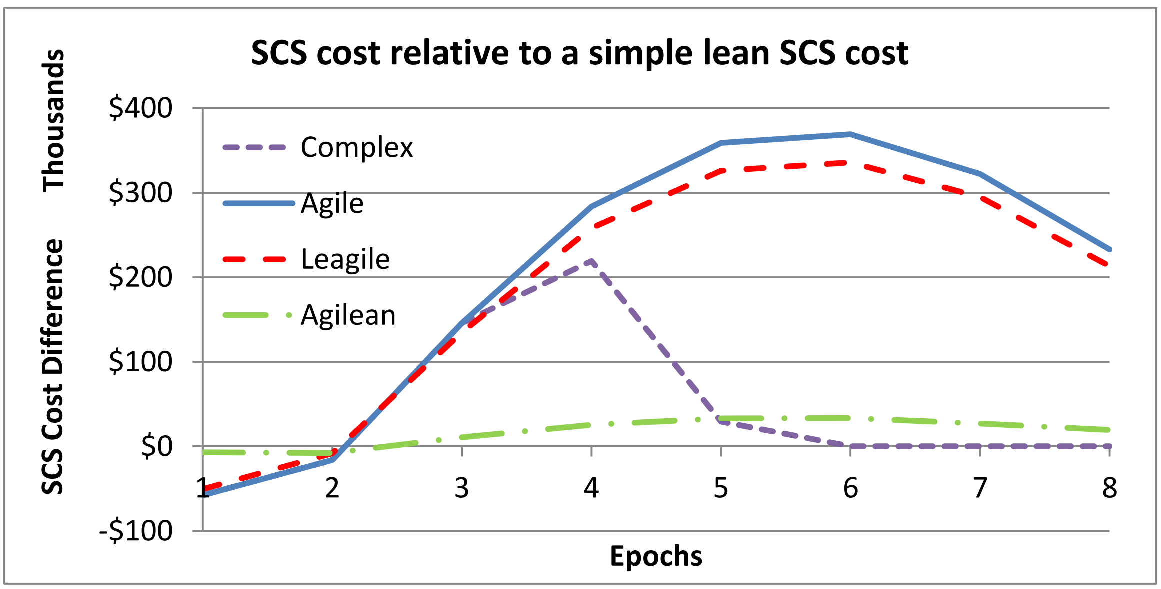


Figure 6.22: Each SCS cost per epoch relative to the simple lean SCS for a scenario with high *RMP*.

For the scenario presented in Table 6.8 and Figure 6.22, if a supply chain wants to evolve the SCS from an agile SCS to a lean SCS, to minimize the cost impact to the supply chain, the demand side of the supply chain should evolve first to an agilean SCS. Then, later, the supply side should evolve to complete the evolution to a lean SCS. In this scenario, the cost differences between an agilean SCS and a leagile SCS can be as high as $300 thousand per epoch. Therefore, with high *RMP* the SCS evolution from an agile SCS to a lean SCS should start with the demand side to evolve to an agilean SCS to avoid potentially significant cost impact when a leagile SCS is employed for this scenario.

6.4.2 Medium *RMP*

The second scenario considered is with medium *RMP*. The cost per epoch for each simple SCS and the complex SCS, as well as the strategy of the complex SCS per epoch are presented in Table 6.9.

Epoch	Lean SCS	Agile SCS	Leagile SCS	Agilean SCS	Complex SCS	Complex SCS	Expected Demand
1	$944	$866	$919	$891	$866	Agile	7,947
2	$4,775	$4,707	$4,765	$4,717	$4,707	Agile	46,453
3	$9,907	$10,019	$9,977	$9,948	$10,019	Agile	100,846
4	$14,594	$14,850	$14,728	$14,716	$14,824	Agilean	151,739
5	$17,593	$17,923	$17,761	$17,756	$17,756	Agilean	185,559
6	$18,220	$18,557	$18,391	$18,387	$18,343	Lean	194,553
7	$16,364	$16,642	$16,506	$16,500	$16,364	Lean	176,781
8	$12,456	$12,662	$12,562	$12,556	$12,456	Lean	136,121
Total Cost	$94,853	$96,226	$95,608	$95,472	$95,336		
Total Cost Difference	$0	$1,373	$756	$619	$483		
Pct. Difference	0.00%	1.45%	0.80%	0.65%	0.51%		

Table 6.9: Medium *RMP* scenario cost ($,000) information for each simple SCS and the complex SCS by epoch.

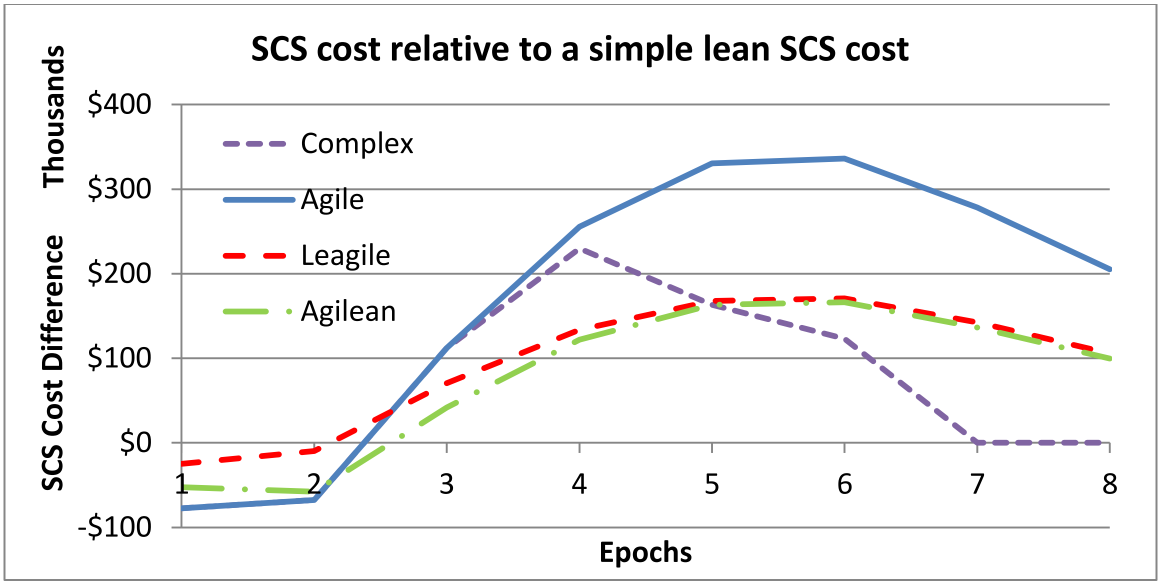


Figure 6.23: Each SCS cost per epoch relative to the simple lean SCS for a scenario with medium *RMP*.

For the scenario presented in Table 6.9 and Figure 6.23 with medium *RMP*, if a supply chain wants to evolve the SCS from an agile SCS to a lean SCS, the relative cost difference of first switching the demand side versus the supply side is very small. From Table 6.9, starting with epoch 4, the first epoch the complex SCS evolves, the cost differences between an agilean SCS and a leagile SCS are at most $12,000 per epoch. Therefore, to evolve the supply chain from an agile SCS to a lean SCS with a medium *RMP* for the scenario considered, the supply chain should most likely base their selection of the side of the supply chain to start with on factors other than cost.

6.4.3 Low *RMP*

The third scenario considered is with low *RMP*. The cost per epoch for each simple SCS and the complex SCS, as well as the strategy of the complex SCS per epoch are presented in Table 6.10.

Epoch	Lean SCS	Agile SCS	Leagile SCS	Agilean SCS	Complex SCS	Complex SCS	Expected Demand
1	$969	$861	$964	$866	$861	Agile	7,947
2	$4,826	$4,711	$4,817	$4,720	$4,711	Agile	46,453
3	$9,955	$10,012	$9,950	$10,017	$10,012	Agile	100,846
4	$14,640	$14,844	$14,637	$14,847	$14,844	Agile	151,739
5	$17,640	$17,918	$17,638	$17,921	$17,918	Agile	185,559
6	$18,269	$18,555	$18,266	$18,559	$18,487	Leagile	194,553
7	$16,410	$16,653	$16,404	$16,660	$16,404	Leagile	176,781
8	$12,492	$12,663	$12,487	$12,669	$12,487	Leagile	136,121
Total Cost	$95,202	$96,216	$95,162	$96,259	$95,723		
Total Cost Difference	$40	$1,054	$0	$1,097	$561		
Pct. Difference	0.04%	1.11%	0.00%	1.15%	0.59%		

Table 6.10: Low *RMP* scenario cost ($,000) information for each simple SCS and the complex SCS by epoch.

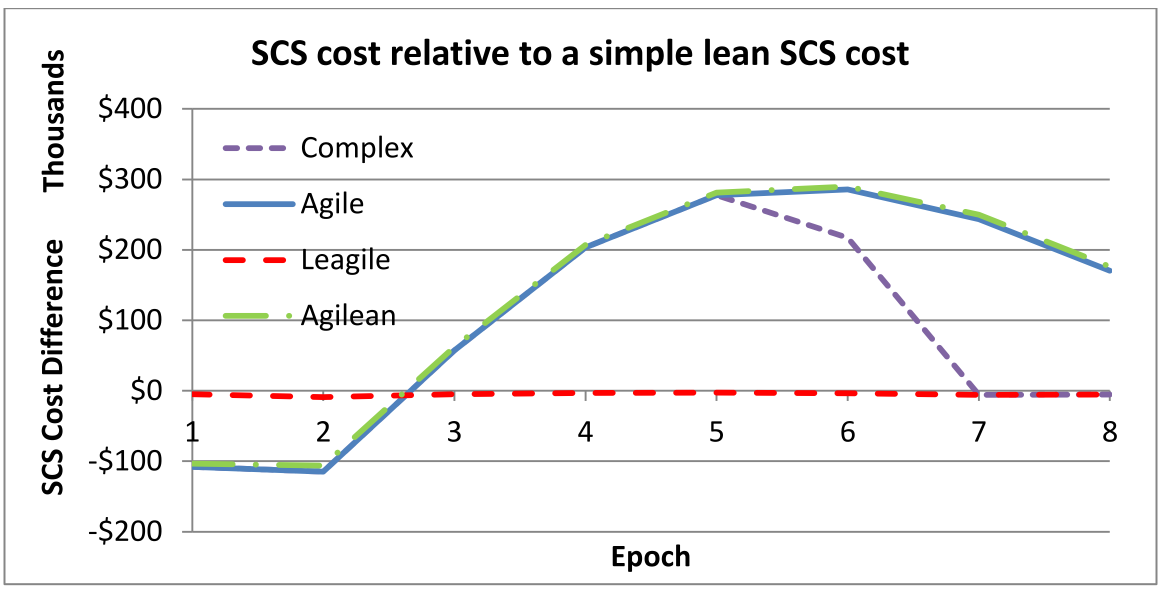


Figure 6.24: Each SCS cost per epoch relative to the simple lean SCS for a scenario with low *RMP*.

For the scenario presented in Table 6.10 and Figure 6.24, if a supply chain wanted to evolve the SCS from an agile SCS to a lean SCS, to minimize the cost impact the supply chain should change the supply side first and evolve to a leagile SCS, and then later, evolve the demand side to complete the evolution to a lean SCS. In this scenario, the cost differences between a leagile SCS and an agilean SCS can be as high as $290 thousand per epoch. Therefore, with low *RMP* the SCS evolution from an agile SCS to a lean SCS should start with the supply side to avoid potentially significant cost impact of using an agilean SCS.

6.5 Summary

The analysis found that for 483 of the 486 (99.4%) scenarios examined (shown in Figures 6.6-6.11) a simple SCS resulted in the same or lower PLC Total Cost than a complex SCS, when PLC Total Cost is determined using a rolling horizon heuristic. The research presented in this chapter supported analytically the research of Randall and Ulrich (2001), Cigolini (2004), Stradtler (2005), Juttner et al. (2006), Vonderembse et al. (2006), and Seuring (2009) that in most cases the SCS of a product should be determined prior to the product's introduction to the market and the SCS should be fixed for the entire PLC. There were only a very few situations identified when the minimum cost solution was to change the SCS during the PLC.

The analysis found for the values considered that when the lean index was high or when the lean index was medium and demand forecast error was either low or medium the simple SCS that resulted in the lowest PLC Total Cost was independent of the length of the PLC and the total expected demand. In addition, the research found for those scenarios where the simple SCS that resulted in the lowest PLC Total Cost was dependent on the length of the PLC, when the PLC length was long, as for a functional product, and total expected demand was increased, then the simple SCS that resulted in the lowest PLC Total Cost moved towards a leaner SCS. In contrast, when the PLC length was short (as for an innovative product) and total expected demand was increased, then the simple SCS that resulted in the lowest PLC Total Cost moved towards a more agile SCS.

The results of the scenario analysis presented in section 6.2 and the examples examined in 6.3 supported the validity of the model presented in this research. For products that were easily classified as functional or innovative (as under the Fisher Model) and when total production costs were split evenly between the supply side and the demand side, then the appropriate simple SCS to minimize PLC Total Cost was a simple lean SCS for a functional product and a simple agile SCS for an innovative product. However, one significant insight provided by this research arises from products that were not easily classified as functional or innovative or when total production costs were not split evenly between the supply side and demand side. This research found that when the majority of total production costs were incurred at the manufacturer, then a simple agilean SCS may result in the lowest PLC Total Cost; and when the majority of total production costs were incurred at the supplier, then a simple leagile SCS may result in the lowest PLC Total Cost.

The analysis presented in section 6.4 demonstrated the financial impact of the decision of which side of the supply chain to evolve first when going from an agile SCS to a lean SCS. The analysis demonstrated that when a supply chain evolved from an agile SCS to a leaner SCS, the supply chain should start with the side of the supply chain where the majority of the costs are incurred.

7. Conclusion

The purpose of this research was to address three fundamental questions related to supply chain strategy selection. The first question (addressed in Chapter 4) focused on the Fisher Model: Under what circumstances does a supply chain with a "Mismatch" of SCS and product type outperform a supply chain with a "Match" of SCS and product type. Specifically, the questions addressed were: "When would an agile SCS minimize the total cost of a supply chain when the product had demand characteristics of a functional product, and when would a lean SCS minimize the total cost of the supply chain when the product had demand characteristics of an innovative product?"

The second question (addressed in Chapter 5) is: When does each SCS minimize the total supply chain cost for a forecast period? To address this question the research first considered the setting where expected demand was constant for the forecast period, and then extended this setting to the impact on the best SCS when expected demand was allowed to increase or decrease linearly over the forecast period.

The third question considered by this research (addressed in Chapter 6) was: Which SCS minimized total supply chain cost over the classical life-cycle of a product? Six different production circumstances were examined.

This research presented an original analytical model of a three echelon supply chain with two inventory points to determine the total cost of each SCS for a forecast period when expected demand and demand forecast error were functions of time (Chapter 3). The first question was examined considering two supply chain strategies (lean SCS and agile SCS), with expected demand and demand forecast error assumed constant for the forecast period. The second question was examined considering four supply chain strategies (lean SCS, leagile SCS, agile SCS, and agilean SCS), with demand forecast error assumed constant and expected demand a linear function of time over the forecast period. The third question was examined considering four simple supply chain strategies (lean SCS, leagile SCS, agile SCS, and agilean SCS) and a complex SCS that combined the simple strategies, with demand forecast error modeled as an exponential decay function with respect to time, and expected demand modeled to mimic the Classical PLC.

7.1 Findings

This research presented an original analytical model to determine the total NPV supply chain cost for a supply chain setting that included three echelons and two inventory points. The convexity of the model was evaluated with the hypothesis *H1*.

To address the first fundamental research question, "Under what circumstances does a supply chain with a misaligned SCS and product type outperform a supply chain with an aligned SCS and product type?" six hypotheses were presented, two to specifically evaluate the question and four to examine the propensity of a supply chain to move towards either a lean SCS or an agile SCS as an aspect of the supply chain was changed.

#	Hypothesis Description	Accepted	Rejected
H1	When demand is constant there are values for the number of ordering periods, N_S^* and N_D^*, which minimizes $C_1(\tau, \delta, \psi, i)$ for the forecast period $[0, T]$.	X	
H2	The total cost of an agile SCS can be less than that of a lean SCS when demand forecast error is low, and an agile SCS becomes more attractive as the ratio of manufacturing cost to purchased material cost decreases, lean index decreases, and cost of capital increases.	X	
H3	The total cost of a lean SCS can be less than that of an agile SCS when demand forecast error is high, and a lean SCS becomes more attractive as the ratio of manufacturing cost to purchased material cost increases, lean index increases, and cost of capital decrease.	X	
H4	As the ratio of total production cost to total order processing cost increases, the supply chain's propensity towards a lean SCS increases.	X	
H5	As the expected daily demand rate increases, the supply chain's propensity towards a lean SCS increases.	X	
H6	When the ratio $\frac{L_{L,S}}{L_{A,S}}$ increases, the supply chain's propensity towards an agile SCS increases.	X	
H7	When the service level of the agile SCS increases, the supply chain's propensity towards a lean SCS increases.	X	

Table 7.1: Summary of hypotheses testing.

To address the second fundamental research question, "Under what combination of supply chain characteristics does each SCS minimize total supply chain cost?", the analysis was completed in two stages. For the first stage the demand forecast error and expected demand were assumed constant over the forecast period, and each of the eighty-one scenarios were evaluated to determine which of the four SCS resulted in the lowest total cost. The analysis showed that a compound SCS (leagile SCS or agilean SCS) was likely to result in the lowest total cost when *RMP* was either low or high. A leagile SCS should be considered when the majority of production costs were located at the supplier and an agilean SCS should be considered when the majority of production costs occur at the manufacturer.

The second stage was accomplished by employing a sensitivity analysis of the findings of the first step with respect to the two aspects of the supply chain that would generally be the most uncertain: expected demand and demand forecast error. The eighty-one scenarios were evaluated at seven levels of expected demand percent change over the forecast period. The SCS that resulted in the lowest SCS was insensitive to a reasonable change in the expected daily demand rate for every scenario except one.

The final part of the sensitivity analysis in stage two examined those scenarios where the SCS that resulted in the lowest total cost was dependent on the level of demand forecast error. In all scenarios examined, as demand forecast error increased the SCS moved towards a more agile SCS.

To address the third fundamental research question, "Which SCS minimized total supply chain cost over the classical life-cycle of a product? ", the analysis considered six product situations. Each product situation was evaluated for the eighty-one scenarios and the PLC total cost was determined using a rolling horizon heuristic. The analysis found that for almost all combinations of scenario and situation that a single SCS over the PLC (simple SCS) would result in the same or lower PLC total cost than a SCS strategy where more than one SCS could be adopted over the PLC (complex SCS). These findings analytically support prior research, that in most cases the SCS of a product should be determined prior to the product's introduction to the market and the SCS should be fixed for the entire PLC.

The research found that the for a large majority of the scenarios, the SCS that resulted in the lowest total cost was independent of both the lengths of the PLC and the total expected demand levels considered. When the simple SCS that resulted in the lowest

PLC total cost was dependent on the length of the PLC or the total expected demand, then the research found: (i) when the PLC length was that of a functional product and total expected demand was increased, then the simple SCS that resulted in the lowest PLC total cost moved towards a leaner SCS, (ii) when the PLC length was that of an innovative product and total expected demand was increased, then the simple SCS that resulted in the lowest PLC total cost moved towards a more agile SCS, (iii) when total expected demand was low and the length of the PLC was increased, a more agile SCS may reduce the PLC total cost of a product, and (iv) when total expected demand was high and the length of the PLC was increased a leaner SCS may reduce the PLC total cost of a product.

The scenario analysis in Chapter 6 demonstrated support for the Fisher Model, in that for those products which can clearly be classified as either functional or innovative, the appropriate simple SCS to minimize PLC total cost was a simple lean SCS and a simple agile SCS, respectively. However, the significant advantage of the model presented in this research was its applicability to scenarios where the product was not easily classified as either functional or innovative. In addition, the versatility of the model allows a supply chain to examine a wide range of scenarios and to evaluate the sensitivity of the total cost to various parameters.

7.2 Managerial insights

The following are key managerial insights from this research, which are limited to the range of parameters and scenarios examined in the dissertation and may not be applicable to settings outside of these conditions.

1. For functional products with stable demand and a low lean index, when the majority of production costs are incurred early in the supply chain or when risk associated with carrying inventory is high, then an agile SCS may result in a lower total cost than a lean SCS.
2. For innovative products with unstable demand and a medium lean index, when the majority of production costs are incurred late in the supply chain or when risk associated with carrying inventory is low, then a lean SCS may result in a lower total cost than an agile SCS.
3. For supply chains where the majority of costs are incurred late in the supply chain, an agilean SCS may minimize total cost.
4. For supply chains where the majority of costs are incurred early in the supply chain a leagile SCS may minimize total cost.
5. For most supply chains, the expected daily demand rate can be assumed constant when determining the SCS that minimizes total cost.
6. With a high lean index or a medium lean index and a low to medium demand forecast error, the SCS that minimized the total cost is independent of the length of the PLC and total expected demand.
7. For supply chains where the SCS that results in the lowest cost is dependent upon the length of the PLC and/or the total expected demand: (i) for products with supply chains where the total expected demand is high and the length of PLC increases, or where the length of the PLC is long and total expected demand increases a leaner SCS may improve total cost, and (ii) for products with supply chains where the PLC lengthens and total expected demand is low or total

expected demand increase and the PLC is short, a more agile SCS may improve total cost.

8. For supply chains that plan to evolve the SCS from an agile SCS to a lean SCS, the supply chain should evolve the side where the majority of production costs are incurred and when production costs are similar for the supply side and demand side, then the supply chain should consider other factors than only cost to determine the side to evolve first.

7.3 Contributions

This research provides a number of contributions to the literature concerning supply chain strategy selection. First, the research developed an original analytical model that accounted for the time value of money in a supply chain setting with three echelons and two inventory points to determine the total NPV supply chain cost. Second, the research describes the supply chain characteristics where a “Mismatch” between SCS and product type may be desirable to minimize costs. Third, the research provides insight into how where costs are incurred in the supply chain (supply side vs. demand side) impacts the selection of the appropriate SCS. Fourth, the research demonstrated when the expected daily demand rate is relatively high, the best SCS to minimize total cost is insensitive to reasonable levels of change in the expected daily demand rate. Fifth, the research provides managerial insights to the impact the length of a PLC and the level of total expected demand has on the appropriate SCS to minimize total cost. Finally, the research presents a new SCS concept, **agilean SCS**, not yet discussed in the literature, and demonstrates when an agilean SCS may be the appropriate SCS to minimize total cost.

7.4 Limitations

There were a number of limitations associated with the research.

1. The model examined a wide range of parameters, but acknowledged that not all possible scenarios were considered and the findings may not be applicable for scenarios outside the range of parameters considered.
2. There may exist locally optimal results within the range of parameters considered that were not discovered.
3. The model was developed as a planning model to analyze expected demand and did not respond dynamically to changes in actual demand.
4. The model was developed and was only effective for supply chains that employ a periodic review inventory replenishment system.
5. The lead time of the supply chain strategies were assumed constant.
6. The model assumed realized demand was normally distributed about expected demand and for some products there could be other distributions that may be more appropriate.
7. The function used to describe the classical PLC was developed for this research and did not necessarily describe the expected demand of all products that had a classical PLC.
8. The classical PLC presented in this research was just one of several product life-cycles that had been discussed in literature and did not necessarily describe the life-cycle of all products.

7.5 Opportunities for future research

Both the area of the supply chain strategy selection and the analytical model developed in this research offer a variety of future research opportunities. For example, a survey methodology could be employed to determine the impact the supply chain and product characteristics presented in this research (*RMP*, lean index, demand forecast error and cost of capital), along with other characteristics, have on practitioners' choices when selecting a SCS for a product. Another opportunity for future research could involve further analysis of parameters affecting the model, but not considered fully in this research (e.g., value of $\beta \neq \gamma$). Although the findings of this research support the validity of the model presented within, a third opportunity for future research is validating the model with real industry supply chain data. A fourth opportunity for future research is determining the optimal complex SCS and optimal simple SCS with mathematical programming that considers relaxed replenishment policy constraints, with the results evaluated against the findings of this research. Another opportunity for future research is considering different definitions of a leagile SCS; for example the model can be restructured to consider the "base and surge" and the Pareto definitions of leagile SCS to provide further insight to the appropriate SCS to minimize total cost. Lastly, the discussion concerning the agilean SCS can be expanded. One possible example of the agilean SCS is Toyota Motors Corporation, where on the demand side of the supply chain 95% of Toyota vehicles are produced to forecasted demand, while the supply side of the supply chain is very agile with many suppliers making multiple deliveries to Toyota assembly facilities daily.

Works cited

Agarwal, A., Shankar, R., & Tiwari, M. (2006). Modeling the metrics of lean, agile and leagile supply chian: An ANP-based approach. *European Journal of Operational Research, 173*, 211-225.

Ahn, H., & Kaminsky, P. (2005). Production and distribution policy in a two-stage stochastic push-pull supply chain. *IIE Transactions, 37*, 609-621.

Aitken, J., Childerhouse, P., & Towill, D. (2003). The impact of product life cycle on supply chain strategy. *International Journal of Production Economics, 85*, 127-140.

Aitken, J., Christopher, M., & Towill, D. (2002). Understanding, implementing and exploiting agilityand leanness. *International Journal of Logistics: Research and Applications, 5*(1), 59-74.

Argelo, S. (1992). *Integral Logistics Structures: Developing Customer Oriented Goods Flow*. (S. Hoekstra, & J. Romme, Eds.) New York, NY: McGraw-Hill.

Aviv, Y. (2001). The effect of collaborative forecasting on supply chain performance. *Management Science, 47*(10), 1326-1343.

Besbes, K., Allaoui, H., Goncalves, G., & Loukil, T. (2012). A two-phase approach for supply chain design with product life cycle and green procurement considerations. *Proceedings of MOSIM'12.* Bordeaux.

Catalan, M., & Kotzab, H. (2003). Assessing the responsiveness in the Danish mobile phone supply chain. *International Journal of Physical Distribution & Logistics, 33*(8), 668-85.

Cheung, K. L., & Lee, H. L. (2002). The inventory benefit of shipment coordination and stock rebalancing in a supply chain. *Management Science, 48*(2), 300-306.

Chiang, W.-y. K., Chhajed, D., & Hess, J. D. (2003). Direct marketing, indirect profits: A strategic analysis of dual-channel supply-chain design. *Management Science, 49*(1), 1-20.

Childerhouse, P., Aitken, J., & Towill, D. (2002). Analysis and design of focused demand chains. *Journal of Operations Management, 20*, 675-689.

Christopher, M. (1992). *Logistics & Supply Chain Management.* London: Pitmans.

Christopher, M., & Towill, D. (2000). Marrying lean and agile paradigms. *Proceedings of EUROMA*, (pp. 114-121). Ghent, Belgium.

Christopher, M., & Towill, D. (2001). An integrated model for the design of agile supply chain. *International Journal of Physical Distribution & Logistics Management, 31*(4), 235-46.

Christopher, M., & Towill, D. (2002). Developing market specific supply chain strategies. *International Journal of Logistics Management, 13*(1), 1-14.

Christopher, M., Peck, H., & Towill, D. (2006). A taxonomy for selectign global supply chain strategies. *The International Journal of Logistics Management, 17*(2), 277-287.

Cigolini, R., Cozzi, M., & Perona, M. (2004). A new framework for supply chain management. *International Journal of Operations & Production Management, 24*(1), 7-41.

Cox, W. J. (1967). Product life cycles as marketing models. *The Journal of Business, 40*(4), 375-384.

CSCMP. (n.d.). *Council of Supply Chain Management Professionals Supply Chain Management*. Retrieved from http://cscmp.org/about-us/supply-chain-management-definitions

de Treville, S., Shapiro, R., & Hameri, A. (2004). From supply chain to demand chain: the role of lead time reduction in improving demand chain performance. *Journal of Operations Management, 21*, 613-627.

Dean, J. (1950). Pricing policies for new products. *Havard Business Review, 28*(6), 45-53.

Delen, D., Hardgrave, B. C., & Sharda, R. (2007). RFID for better supply-chain management through enhanced information visibility. *Production and Operations Management, 16*(5), 613-624.

Disney, S. M., & Towill, D. R. (2003). On the bullwhip and inventory variance produced by an ordering policy. *Omega: The International Journal of Management Science, 31*, 157-167.

Disney, S. M., & Towill, D. R. (2003). Vendor-managed inventory and bullwhip reduction in a two-level supply chain. *International Journal of Operations& Production Management*, *23*(6), 625-651.

Disney, S., & Naim, M. P. (2004). Assessing the impact of e-business on supply chain dynamics. *International Journal of Production Economics, 89*, 109-118.

Disney, S., Warburton, R., & Zhong, Q. (2013). Net present value analysis of the economic production quantity. *IMA Journal of Management Mathematics, 24*(4), 423-435.

Ernst, R., & Kamrad, B. (2000). Evaluation of supply chain structures through modularization and postponement. *European Journal of Operational Research, 124*, 495-510.

Fisher, M. (1997). What is the right supply chain for your product. *Harvard Business Review, 75*(2), 105-16.

Franca, R., Jones, E., Richards, C., & Carlson, J. (2010). Multi-objective stochastic supply chain modeling to evaluate tradeoffs between profit and quality. *International Journal of Production Economics*, *127*, 292-299.

Gavirneni, S., Kapuscinski, R., & Tayur, S. (1999). Value of information in capacitated supply chains. *Management Science, 45*(1), 16-24.

Goldsby, T., Griffis, S., & Roath, A. (2006). Modeling lean, agile, and leagile supply chain strategies. *Journal of Business Logistics*, *27*(1), 57-80.

Grubbstrom, R. (1980). A principle for determining the correct capital costs of work-in-progress and inventory. *International Journal of Production Research, 18*(2), 259-271.

Guillen, G., Mele, F., Bagajewicz, M., Espuna, A., & Puigjaner, L. (2005). Multiobjective supply chain design under uncertainty. *Chemical Engineering Science, 60*, 1535-1553.

Gupta, D., & Benjaafar, S. (2004). Make-to-order, make-to-stock, or delay product differentiation? A common framework for modeling and analysis. *IIE Transactions, 36*, 529-546.

Harris, G., Componation, P., & Farrington, P. (2010). An exploration of Fisher's framework for the alignment of supply chain strategy with product characteristics. *Engineering Management Journal*, *22*(4), 31-42.

Hashemi, A., Butcher, T., & Chhetri, P. (2013). A modeling framework for the anlysis of supply chain complexity using product design and demand characteristics. *International Journal of Engineering, Science and Technology, 5*(2), 150-164.

Herer, Y., Tzur, M., & Yucesan, E. (2002). Transshipments: An emerging inventory recourse to achive supply chain leagility. *International Journal of Production Economics, 80*, 201-212.

Hilletofth, P. (2009). How to develop a differentiated supply chain strategy. *Industrial Management & Data Systems, 109*(1), 16-33.

Holmstrom, J., Korhonen, H., Laiho, A., & Hartiala, H. (2006). Managing product introductions across the supply chain findings from a development project. *Supply Chain Management: An International Journal, 11*(2), 121-130.

Huang, S. H., Uppal, M., & Shi, J. (2002). A product-driven approach to manufacturing supply chain selection. *Supply Chain Managment: An International Journal, 7*(3/4), 189-99.

Jeong, I.-J. (2011). A dynamic model for the optimization of decoupling point and production planning in a supply chain. *International Journal of Production Economics, 131*, 561-567.

Juttner, U., Godsell, J., & Christopher, M. (2006). Demand chain alignment competence - delivering value through product lfe cycle management. *Industrial Marketing Management, 35*, 989-1001.

Khan, O., Christopher, M., & Creazza, A. (2012). Aligning product design with the supply chain: A case study. *Supply Chain Management: An International Journal, 17*(3), 323-336.

Kilbi, W., Martel, A., & Guitouni, A. (2010). The design of robust value-creating supply chain networks: A critical review. *European Journal of Operational Research, 203*, 283-293.

Kim, B. (2000). Coordinating an innovation in supply chain management. *European Journal of Operational Research, 123*, 568-584.

Kim, S., & Ha, D. (2003). A JIT lot-splitting model for supply chain management: Enhancing buyer-suppier linkage. *International Journal fo Production Economics, 86*, 1-10.

Lamming, R. C., Johnsen, T., Zheng, J., & Harland, C. (2000). An initial classification of supply networks. *International Journal of Operations & Production Management, 20*(6), 675-91.

Lee, H. L. (2002, Spring). Aligning supply chain strategies with product uncertainties. *California Management Review, 44*(3), 104-119.

Lee, H., So, K., & Tang, C. (2000). The value of information sharing in a two-level supply chain. *Management Science, 46*(5), 626-643.

Li, D., & O'Brien, C. (1999). Integrated decision modelling of supply chain efficiency. *International Journal of Production Economics, 59*, 147-157.

Li, D., & O'Brien, C. (2001). A quantitative analysis of relationships between product types and supply chain strategies. *International Journal of Production Economics, 73*, 29-39.

Lin, B., Collins, J., & Su, R. (2001). Supply chain costing: an activity-based perspective. *International Journal of Physical Distribution & Logistics Management, 9*(10), 702-713.

Lo, S., & Power, D. (2010). An empirical investigation of the relationship between product nature and supply chain strategy. *Supply Chain Management: An International Journal, 15*(2), 139-153.

Mason-Jones, R., Naylor, B., & Towil, D. R. (2000a). Engineering the leagile supply chain. *International Journal of Agile Management Systems, 2*(1), 54-61.

Mason-Jones, R., Nayor, B., & Towill, D. (2000b). Lean, agile, or leagile? Matching your supply chain to the marketplace. *International Journal of Production Research, 38*(17), 4061-4070.

Naim, M. (2006). The impact of net present value on the assessment of the dynamic performance of e-commerce enabled supply chains. *International Journal of Production Economics, 104*, 382-393.

Naim, M., & Gosling, J. (2011). On leannes, agility and leagile supply chains. *International Journal of Production Economics, 131*, 342-354.

Naylor, J., Naim, M., & Berry, D. (1999). Leagility: Integrating the lean and agile manufacturing paradigms in the total supply chain. *International Journal of Production Economics, 62*, 107-118.

Ohno, T. (1988). *The Toyota Production System; Beyond Large Scale Production.* Portland, OR: Productivity Press.

Olhager, J. (2003). Strategic positioning of the order penetration point. *International Journal of Production Economics, 85*, 319-329.

Ouyang, Y. (2007). The effect of information sharing on supply chain stability and the bullwhip effect. *European Journal of Operational Research, 182*, 1107-1121.

Pero, M., Abdelkafi, N., Sianesi, A., & Blecker, T. (2010). A framework for the alignment of new product development and supply chains. *Supply Chain Management: An International Journal, 15*(2), 115-128.

Porter, M. (1985). *Competitive Advantage.* New York, NY: The Free Press.

Qi, Y., Boyer, K., & Zhao, X. (2009, November). Supply chain strategy, product characteristics, and performance impact: Evidence from Chinese manufacturers. *Decision Sciences, 40*(4), 667-695.

Qi, Y., Zhao, X., & Sheu, C. (2011). The impact of competitive strategy and supply chain strategy on business performance: The role of environmental uncertainty. *Decision Sciences, 42*(2), 371-389.

Raghunathan, S. (2001). Information sharing in a supply chain: A note on its value when demand is nonstationary. *Management Science, 47*(4), 605-610.

Ramdas, K., & Spekman, R. (2000). Chain or shackles: Understanding what drives supply-chain performance. *Interfaces, 30*(4), 3-21.

Randall, T., & Ulrich, K. (2001). Product variety, supply chain structure, and firm performance: Analysis of the U.S. bicycle industry. *Management Science, 47*(12), 1588-1604.

Randall, T., Morgan, R., & Morton, A. (2003). Efficient versus responsive supply chain choice: An empirical examination of influential factors. *The Journal of Produt Innovation Management, 20*, 430-443.

Riddle, D. F. (1979). *Calculus and analytic geometry.* Belmont, CA: Wadsworth Publishing Company, Inc.

Rink, D., & Swan, J. (1979). Product life cycle research: A literature review. *Journal of Business Research, 7*(3), 219-242.

SCC. (1999). *Supply chain operations reference (SCOR) model.* Cyprus, TX: Supply Chain Council, Inc. Retrieved from http://supply-chain.org/f/Web-Scor-Overview.pdf

Selldin, E., & Olhager, J. (2007). Linking products with supply chains: testing Fisher's model. *Supply Chain Management: An International Journal, 12*(1), 42-51.

Seuring, S. (2009). The product-relationship matrix as framework for strategic supply chain design based on operations theory. *International Journal of Production Economics, 120*, 221-232.

Sharifi, H., Ismail, H., Qiu, J., & Tavani, S. (2013). Supply chain strategy and its impact on product and market growth strategies: A case study of SMEs. *International Journal of Production Economics, 145*, 397-408.

Simchi-Levi, D., Kaminsky, P., & Simchi-Levi, E. (2008). *Designing and managing the supply chain concepts,strategies, and case studies* (3rd ed.). New York, NY, USA: McGraw-Hill/Irwin.

Stadtler, H. (2005). Supply chain management and advanced planning - basics, overview and challenges. *European Journal of Operational Research, 163*, 575-588.

Stratton, R., & Warburton, R. (2003). The strategic integration of agile and lean supply. *International Journal of Production Economics, 85*, 183-198.

Sun, S., Hsu, M., & Hwang, W. (2009). The impact of alignment between supply chain strategy and environmental uncertainty on SCM performance. *Supply Chain Management: An International Journal, 14*(3), 201-212.

Thonemann, U. W. (2002). Improving supply-chain performance by sharing advance demand information. *European Journal of Operational Research, 142,* 81-107.

Towill, D., & Christopher, M. (2002). The supply chain strategy conundrum: To be lean or agile or to be lean and agile. *International Journal of Logistics: Research and Applications, 5*(3), 299-309.

Tsay, A. A., & Lovejoy, W. S. (1999). Quantity flexibility contracts and supply chain performance. *Manufacturing & Service Operations Management, 1*(2), 89-111.

Vonderembse, M., Uppal, M., Huang, S., & Dismukes, J. (2006). Designing supply chains: Toward theory development. *International Journal of Production Economics, 100*, 223-238.

Wang, G., & Huang, S. H. (2004). Product-driven supply chain selection using integrated multi-criteria decision-making methodology. *International Journal of Production Economics, 91*(1), 1-15.

Womack, J., & Jones, D. (1996). *Lean Thinking.* New York: Simon and Schuster.

Womack, J., Jones, D., & Roos, D. (1990). *The Machine that Changed the World.* New York: Macmillan.

Wong, C., Arlbjorn, J., Hvolby, H., & Johnansen, J. (2006). Assessing responsiveness of a volatile and seasonal supply chian: A case study. *International Journal of Production Economics, 104,* 709-721.

Xu, K., Dong, Y., & Evers, P. (2001). Towards better coordination of the supply chains. *Transportation Research Part E, 37*, 35-54.

