Supply Chain Strategy:

Further Development on how to Match Product Type with Supply Chain Design

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Abstract

An effective competitive supply chain strategy is supposed to create maximum value to the customer. A key element of success in designing such a strategy is to align all supply chain decisions (that add cost) with demand attributes (that describe the value). Achieving and maintaining the alignment, despite being studied and practised for a long time, has never been as crucially important as it is in today's extremely competitive business environment. This research explores the alignment as well as its influencing factors and aims to provide a constructive guide on how to achieve it by making the right decisions on strategy design.

We analyse how a set of major product and demand characteristics, i.e., demand variability, profit margin, and product life cycle, impact strategic decisions on inventory and sourcing. The objective is to demonstrate the extent to which it is beneficial, in terms of the expected profitability, for the firms to effectively adjust their decisions with the product characteristics when designing their supply chain strategy. The analyses are conducted through mathematical optimization of a two-echelon supply chain that comprises a manufacturer and a retailer. While doing the analyses, a further contribution is made to the fundamental inventory management system, i.e., continuous review, by developing a bi-objective optimization model based on order quantity and lead time.

As a special case of supply strategy and demand alignment, we study the dual serving problem, where a supplier should make a choice between a group of (routine) customers whose demand is small but stable and another group of (random) buyers whose demand is large but sporadic, or a combination of both. This problem has recently become a challenge in the retail industry especially with the growth of online daily deals platforms. We address the challenge from an inventory management perspective to investigate the optimal choice and settings of the dual serving strategy. Particularly, we formulate and analyze two different alternative choices of serving strategy, namely, aggregation and protection. Our comparative analysis identifies the winning strategy under different settings of demand and economic parameters.

Dedication

This thesis is dedicated

to my parents, who I owe any achievement in my life,

to my wife, Mozhgan, who I love and owe my success,

to my son, Nikan, whose smile is my life.

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Chapter 1

Introduction

A key challenge in operations management is how to effectively design a supply chain structure that is in alignment with the company's business model. This is of particular importance "in today's world of international trade and global competition, where increasingly supply chains compete rather than individual firms and products" (Mangan and Lalwani 2016, p.34). The competition is in fact for achieving higher customer satisfaction, which improves the sales and market share, at minimum total cost, hence supply chain decisions seem to play a crucial role in a company's competitiveness.

The aim of this study is to explore, when looking from the lens of market requirements, how the strategy of a supply chain affects the expected total cost. In particular, we evaluate whether and how a match between the choice of supply chain strategy (i.e., efficient or responsive) and demand characteristics (i.e., demand variability, profit margin, and product life cycle) leads to any cost savings. Although the literature shows that similar evaluation has been undertaken before, since the analysis were mostly based on empirical analysis and the outcomes were various (dependent on the cases studied) and sometimes contradicting, we do our analysis using a mathematical methodology.

In this chapter, we first review the definition and fundamental concepts of business and manufacturing strategy and supply chain design, which (in the manufacturing sector) need to be in a strategic fit, and how we can align them. Then, outlining the objectives of this research in detail, we explain our analytical approach towards addressing the challenge of designing effective supply chain strategies that best match the demand and product characteristics. This chapter concludes by providing an overview of what is going to appear in the following chapters as well as describing how each chapter contributes to answering the research questions.

1.1 Business Strategy

Almost 50 years ago, Skinner (1969) claimed that many US manufacturers lack a proper connection between manufacturing decisions and corporate strategy. He suggested a new "top-down" approach (in contrast to Fredrick W. Taylor's conventional bottom-up production management system) that starts with a systematic collaboration of manufacturing engineers, executives, and top management in order to determine a "competitive strategy". This strategy needs to be designed based on trade-offs between cost, quality, time, and customer satisfaction. The US manufacturers' failure to make such trade-offs was further highlighted by Skinner (1974), who argued that companies should first prioritise their competitive capabilities and explicitly determine what they can really compete on, and then set up a "focused factory" to support their competitive strategy. Subsequent studies further developed the principles and applications of these four main competitive priorities/capabilities, namely: cost, quality, flexibility, and delivery (Wheelwright 1984, Hayes and Wheelwright 1984, Fine and Hax 1985, Roth and Velde 1991, Swink and Way 1995). A very simple and short definition of the priorities is as follows:

- Cost: providing low-cost products
- Quality: providing high-quality products
- Flexibility: providing products according to a variety of requirements
- Delivery: providing products quickly and on time

After a comprehensive review of the literature, Ward et al. (1990) concluded that innovation is a fifth dimension, which was later supported by some other researchers (Noble 1995, 1997, Santos 2000). The quality of service (Zhao et al. 2002) and improvement capability (Demeter et al. 2011) were other nominees for additional dimensions. A synthesis of the manufacturing competitive priorities literature by Vickery et al. (1997) summarised a list of nine dimensions, namely, product flexibility, volume flexibility, low production cost, new product introduction, delivery speed, delivery dependability, quality, product reliability, and design innovation. However, it is possible to categorise all these nine dimensions into the four original ones (e.g., by defining quality broadly), which are the key priorities considered in the literature (Boyer and Lewis 2002). In the following paragraphs, we concisely review the importance and the implication of each of the four competitive priorities of cost, quality, flexibility, and delivery.

1.1.1 Cost

According to Porter's (1985) typology of competitive strategies, "cost leadership" is the ability of a firm to successfully underprice its competition. This can be accomplished through efficiency that maximises useful outputs from total inputs. There are many cost centres, e.g., raw material, labour, working capital, overhead, etc., that can be controlled to reduce the total cost in a firm, which can then be passed on to the customer in terms of decreased price. In general, having cost as a company's first competitive priority requires techniques for increasing efficiency and productivity, a high utilisation of resources, eliminating waste, minimising inventory levels, and almost certainly a lean production system. Lean manufacturing via eliminating "muda", anything which does not add value to customer, was the way that Taiichi Ohno (1988) approached efficiency when establishing the Toyota Production System. Defects, transportation, unnecessary inventory, inappropriate processing, and waiting are examples of muda which only add cost. We discuss lean production further in the next chapter.

Economies of scale is another technique that generally reduces the unit cost by raising the volume and lowering the variety (of products, components, tools, etc.). When applying economies of scale, a cost-efficient strategy is often best suited to commodity-type products that customers typically purchase based on the price in the market.

A good example of a cost-efficient firm is Aldi, an international supermarket chain with mainly food products. They compete on price by adopting some cost-saving practices, such as: using very simple basic facilities (to keep overhead costs down), private labelling (to avoid high branding costs), open carton displaying (to avoid special shelving costs), offering a limited range of goods (around 700 compared with 25,000 to 30,000 items in conventional supermarket chains), using rental carts, and providing no grocery bags (Slack et al. 2013). The types of products selected, the operations/inventory decisions, and the marketing activities are all aligned with the firm's competitive strategy.

There is usually fierce competition in the low-cost segment of the market because only one company can offer the lowest price, which determines the selling price in the whole market. For instance, when Wal-Mart entered Canada in 1994, Zellers, a Canadian discount retailer, lost its challenge to keep its leading position in the low-price market[1] and ended up closing all stores in 2013. It simply did not have the level of efficiency of Wal-Mart (in part because of its smaller scale) and hence could no longer successfully occupy the discount retail store niche in Canada.

1.1.2 Quality

A company's perspective on quality reflects how it thinks about customers, competition, and the business environment (Belohlav 1993). Linking quality to strategy was perhaps best formulated by Porter (1980) as "differentiation", which means creating a value that is known uniquely industrywide. Therefore, quality as a competitive strategy should lead a company to a distinguishing position through delivering a product or service that consistently conforms to, or exceeds, customers' needs.

From a focus on meeting expectations, the interpretation of quality has evolved and developed to include different dimensions, such as, performance, features, conformance, durability, serviceability, aesthetics, and perceived quality (Garvin 1987, 1996). However, depending on the industry type/sector, additional dimensions are sometimes discussed in empirical studies to assess firms' abilities towards quality assurance more comprehensively. For instance, Zhao et al. (2002) added two new dimensions: reducing environmental damage and improving working conditions and safety. High quality means that not only should the product be systematically designed according to appropriate specifications, but also that the processes that produce this product need to be capable of consistently delivering defect-free outputs. This is the essence of Deming's (1986) 14 principles that are typically referred to as the key reference to total quality management (TQM) (Feigenbaum 2002).

[1] "Zellers Is Stretched in Apparel-Rack War. Analysts Suggest Strategies for Battling Wal-Mart", Winnipeg Free Press, August 19, 2002, B6.

According to Powel (1995), even if the main features of TQM, such as quality training, process improvement, and benchmarking, are not perfectly implemented, the intangible results of following TQM ideology will create advantages that lead to outperformance over rivals.

Apart from the competitiveness (or differentiation) that quality commitments can create, they can also significantly decrease costs because they potentially prevent waste (muda). Poor quality incurs high internal and external costs of appraisal to fix failures (Tsai and Hsu 2010). However, this does not mean that zero-defect leads to zero cost as the total cost of quality will increase by prevention/inspection plans. There are various theories and models on how to control the cost of quality, but from a classical view, a trade-off between corrective and preventive costs needs to be made for minimising total quality costs (Castillo-Villar et al. 2012).

There are many helpful quality management tools such as statistical process control (SPC), six sigma (6σ), quality function deployment (QFD), failure mode and effect analysis (FMEA), ISO 9000 series of quality management systems, etc., that firms can adapt to differentiate themselves in the market by quality. However, the crucial point is that the decisions on quality tools have to be made in alignment with the firm's strategic plan and what is demanded by their customers, otherwise the firms will not gain what is expected from the implementation of the quality programs. As cited by Ettlie (1997), research by Buran (1994) has shown that quality programs appear to have failed to meet expectations in two-thirds of the US firms. Also, over 85% of ISO 9000 registrants think it will take eight years or more to recover their costs.

1.1.3 Flexibility

The capability of adapting to new, different, or changing requirements is usually defined as flexibility. How much faster a company responds to market changes than other competitors shows its flexibility competence. The higher it is, the greater global reach and better performance that should result (Fawcett et al. 1996). Fundamentally, flexibility is regarded as process flexibility, altering a production line and related manufacturing facilities, and product flexibility, switching among variety of product designs according to customers' needs, and the main goal is to achieve managerial operating flexibility, which in turn enables strategic adaptability (Trigeorgis 1996).

From a strategic view, flexibility is not only an adaptive response to environmental uncertainties (Swamidass and Newell 1987), but also has a proactive function for creating uncertainties to challenge competitors. However, the level and the type of flexibility (e.g., range or volume) should fit the environmental dynamism (Anand and Ward 2004). To introduce and manage flexibility in an effective manner, Gerwin (1993) identified seven dimensions for flexibility, namely, product mix, volume, changeover, modification, rerouting, material, and sequencing. Based on a review on the literature, De Toni and Tonchia (1998) provided an extensive discussion on the classifications and dimensions of manufacturing flexibility, and stated the need for further research on the measurement of flexibility. A vast majority of unsuccessful flexibility-improvement efforts in many industries was because of the managers' failure to identify precisely what kind of flexibility was needed, how to measure it, or which factors most affected it (Upton 1995).

At the operational level, flexibility typically requires general-purpose equipment, small batch production, skilled decision makers, organic organisation design, and feedback control systems (Ebben and Johnson 2005). Special technologies, however, can sometimes better operationalise flexibility. For example, Paris Miki, an up-market eyewear retailer that has the largest number of eyewear stores in the world, uses its own "Mikissimes Design System" to capture and digitalise each customer's facial characteristics, and then through a certain process, offers a customised design for the customer in one hour (Slack et al. 2013).

From a technological perspective, flexible manufacturing systems (FMS) have been applied to a broad context in which automation, computer aided design and manufacturing (CAD/CAM), material handling systems (MHS), etc. are integrated (Buzacott and Yao 1986). Further development of FMS by the use of various advanced manufacturing technologies has led to focused flexibility manufacturing systems (Tolio 2008). Additive manufacturing (3-D printing) technology, for example, is one highly flexible tool that has the potential to revolutionise many industries very quickly, not only by its extremely high customisation capacity, but also by offering great efficiency. Local Motors recently demonstrated that it can print a good-looking roadster from bottom to top in 48 hours. Although when it goes into production, it will be priced at approximately $20,000, but, if the cost of 3-D equipment and material falls, the remaining advantage of economies of scale in the traditional methods will disappear (D'Aveni 2015).

1.1.4 Delivery

The time between a customer's order for products/services and receiving them is called lead time and is typically known as the main factor in the quality of delivery. Inevitably, the faster the delivery is the more beneficial it is to both customers (e.g., less cost, more convenience, and saved time) and the company (e.g., less inventory, less risk, and higher turnover). However, some believe that a reliable delivery, which means providing the right product at the right time and place, is perceived as a good delivery, even if the promised date is far in the future (Ward et al. 1998). In fact, firms aim to compete on (and customers ask for) the ideal combination of both fast and on-time delivery.

Fast delivery requires programmes for shortening lead times, production cycle, and processing times, while reliable delivery requires reducing process variability and unplanned delays with an accurate forecasting/scheduling to meet delivery promises to the customer (Handfield and Pannesi 1992). If it is not possible to accomplish both delivery speed and delivery reliability simultaneously, firms should prioritise what is more crucial to the customer (Hill and Hill 2012), or if both are vitally important, as indeed is the case for some service companies, these could be set as two separate objectives (Roth and Miller 1992, Slack and Lewis 2015, Spring and Boaden 1997). Slack and Lewis (2015) believe that speed of delivery is an elapsed time of the total process from customer's awareness of need for a product or service to a satisfying installation. Dependability of delivery, however, equals delivery due date minus actual delivery time. Thus, zero means on-time delivery, positive means early delivery, and negative means late delivery.

In contrast, Beckman and Rosenfield (2008) blended delivery performance and flexibility to define a broader dimension, "availability". This refers to making products or services ready at the time customers need them, rapidly introducing new products, and offering a variety of products. They measure delivery performance (as a part of availability) by percentage of on-time shipments, average delay, and expediting response time. Some more potential measures are quality of exchanged information, percentage of in-transit goods, number of faultless notes invoiced, and flexibility of delivery system to meet a particular customer's need (Gunasekaran et al. 2001).

Many studies demonstrated how companies can benefit from making delivery (speed and reliability) a distinctive competence. For instance, Fawcett et al. (1997) empirically validated that not only do delivery capabilities have a strong positive influence on a firm's performance, but also that information availability and planning sophistication significantly improve delivery performance. Guiffrida and Nagi (2006) evaluated delivery performance of supply chain planning by a cost-based model. Financial consequences of untimely delivery were formulated by incorporating the time value of money into the evaluation process. The model justifies the capital investment required for delivery improvement through variability and lead time reduction. Intuitively, it is clear that high delivery performance will lower overhead and processing costs, since less inventory and work in process will be required.

1.2 Manufacturing Strategy

To determine a correct manufacturing strategy, Hill (1993) believes a company should first identify the minimum market entry requirements that allow them to present their product/service. He termed these requirements "order qualifiers", which determine a baseline of business qualities for the company. Then, to win the competition in the market, the firm needs some capabilities/features that distinguish its performance amongst its rivals. These are called "order winners", which determine the company's competitive advantage. Identifying both order qualifiers and order winners logically leads to the specifications of a correct manufacturing strategy. For instance, a study on the implementation of TQM in US manufacturers suggested that quality-related conformance has turned to be an order qualifier, while an order winner is quality characteristics that are related to features and aesthetics. Thus, when all the available alternative products meet conformance standards, the design features and aesthetics create a competitive advantage for firms to win consumers' orders. (Flynn et al. 1995).

It is important to note that order qualifiers/winners may differ from one market to another. An order winner, e.g., a full 2-year warranty for all products, in one market might be an order qualifier in another market, e.g., where the warranty is compulsory by regulations, or when all rivals offer such a warranty. Moreover, in a certain market, some order winners may become order qualifiers over time as the customers' needs gradually alter (Rosen and Karwan 1994). For instance, in most marketplaces, conformance quality was an order winner many years ago, but currently it is more like an order qualifier, and instead, criteria such as flexibility, responsiveness, customisation, and, particularly, innovation are playing the role of order winners (Laosirihongthong and Dangayach 2005, Prajogo et al. 2007).

A study in mainland China showed that producing low price/cost products is no longer the first priority of Chinese companies, but instead, providing reliable products and services was predicted to be Chinese companies' main concern in the next five years. This is because the majority of surveyed companies ranked quality, service, innovativeness, and flexibility as the most important objectives in the next five years, and cost was ranked the least (Zhao et al. 2002). This perhaps means that order winners in the Chinese market are changing from low price to high quality. According to the empirical analysis that Ward et al. (1995) carried out on Singapore's market, delivery performance, flexibility (based on innovation and new technologies), and quality were order winners there.

The identification of order qualifiers and order winners should lead to an appropriate manufacturing strategy that defines how business priorities need to be addressed at strategic and operational levels. There is sufficient empirical evidence showing that the existence of such a manufacturing strategy positively affects a company's performance and competitiveness, e.g., quality of plant performance (Brown 1998), return of sale (Demeter 2003), or sale growth and market share (Ward and Duray 2000). On the other hand, failure to fit the product profile with the manufacturing strategy appears to have a significant negative impact on market share (da Silveira 2005). Nevertheless, defining a manufacturing strategy does not guarantee the success of a business, the ability to actually operationalise the strategy is also important to become a winner of the market competition (Spring and Boaden 1997).

1.3 Multiple Objectives and Trade-offs

There are different approaches that companies can adopt to decide on an appropriate manufacturing strategy based on the alternative competitive priorities (i.e., cost, quality, flexibility, and delivery). There is debate in the literature on whether trade-offs are a useful concept for setting priorities or whether a cumulative or integrative approach is best (Boyer and Lewis 2002).

The idea of a trade-off means improving operations towards a specific dimension requires sacrificing other performance dimension(s). For instance, if the quality of raw material is lowered to reduce the total cost (in a cost-efficient strategy), the quality of finished products will likely diminish as well. Or, the advantage of economies of scale for cost efficiency will result in the disadvantage of low variety of products (low flexibility in range). This approach was first offered by Skinner (1969; 1974), who particularly looked at efficiency and flexibility as two mutually exclusive strategies, and has been extensively supported (Hayes and Wheelwright 1984, Garvin 1993, Randall et al. 2003). This approach claims that "it is difficult (if not impossible) and potentially dangerous for a company to try to compete by offering superior performance along all these dimensions [cost, quality, flexibility, and delivery]." (Hayes & Wheelwright 1984, p. 141)

In contrast, some believe that global competition has forced companies to improve themselves along all dimensions (Schonberger 1990, Szwejczewski et al. 1997). Also, the advantage of advanced technologies allows for simultaneous development on multiple dimensions (Corbett and Wassenhove 1993). As a result, many state that nowadays companies should use cumulative or integrative models for setting their competitive priorities (Vokurka et al. 2002, Flynn and Flynn 2004). Supporting the cumulative models, some empirical studies reported a positive correlation among businesses' priorities (Roth and Miller 1992, Noble 1995), and some others provided practical suggestions, e.g., how to consecutively build different manufacturing capabilities (quality, delivery, cost, and flexibility) in a sequential model (Ferdows and Meyer 1990, Vokurka and Fliedner 1998).

This perceived conflict is often explained using the concept of an "efficient/performance frontier", which is defined as the maximum performance that can be achieved in a manufacturing/operations unit given a set of performance dimensions (Schmenner and Swink 1998). Thus, companies that are not on the frontier can improve all dimensions simultaneously, while those on the frontier indeed face a trade-off (until technology improves). Such a frontier also identifies firms or groups with performance that dominate other firms' performance. This can be used among the firms in a certain industry, so that both 'superior' and 'inferior' firms will try for improvement by either making a trade-off among performance objectives or increasing the cumulative effectiveness of multiple objectives (Slack et al. 2013).

Further, the competitive dimensions/priorities could be concurrently regarded for improvement although at different rates (Hayes and Pisano 1996). Based on a survey of 110 American plants, which have implemented advanced manufacturing systems, Boyer and Lewis (2002) found that they make trade-offs among competitive priorities. Another empirical study on a sample of Japanese companies confirmed that none of them used a single dimension for strategy, and rather they all put emphasis on multiple priorities, cost and quality in particular (Reitsperger et al. 1993).

Apart from the approach that a company chooses for strategic planning, there is a broad agreement that its competitive strategy should have a composition of the priorities (Adam and Swamidass 1989, Leong et al. 1990). It seems that being excellent in only one dimension (e.g., low cost/price) is not enough in a competitive market where there are more than one best competitor in a specific dimension, for instance, when more than one alternative of a certain product are available at the cheapest price, quality or delivery will be the determinant. Therefore, according to Hill (1993), companies should target several objectives, some of which are needed to enter competition (order qualifiers), and some others are required to win the competition.

Another example of an operations strategy framework is the "transitional solution" which analyses companies' global competitiveness in three dimensions; global integration, national responsiveness, and worldwide learning to win the competition in global markets (Bartlett and Ghoshal 1999). As a facilitator tool for the transitional solution, the "model factory concept" was developed by Rudburg and West (2008) to design a global operations strategy through blending cost competitiveness, flexibility, and innovativeness.

A final example is Van Mieghem's (2008) framework that formulates operations strategy from a "top-down and outside-in" perspective, which dictates the concept of strategic fit in an organisation. This results in an operations strategy that "inextricably" links company's competences (what it does well with resources and processes) and its environment (what the market demands and what competitors offer) (Collis and Montgomery 1995). A more detailed discussion on strategic fit/alignment is presented in the next sub section.

1.4 Strategic Alignment

An effective operations strategy not only has to be well-fitted to the firm's environmental conditions, i.e., customers, market, and competitors, but should also be aligned with operations and processes inside the organisation. This strategic alignment leads to correct decisions at all organisational levels and, hence, will result in a better overall performance. Interestingly, research shows that the fit of the operational elements with the business strategy has a greater importance than the particular choice of strategy (Smith and Reece 1999).

Slack et al.'s (2013) framework for blending the four different perspectives on operations strategy, namely, top-down reflection, bottom-up emergence, market requirements translation, and operations capabilities identification, well demonstrates the concept of strategic alignment. As displayed in Figure 1.1, the framework simply depicts how different parts of an organisation should contribute to formation of aligned operations strategy. According to Van Mieghem (2008), the goal of strategy is value maximisation, which can be successfully achieved if the organisational structure and operational system follow the strategy. This accomplishment has several principles:

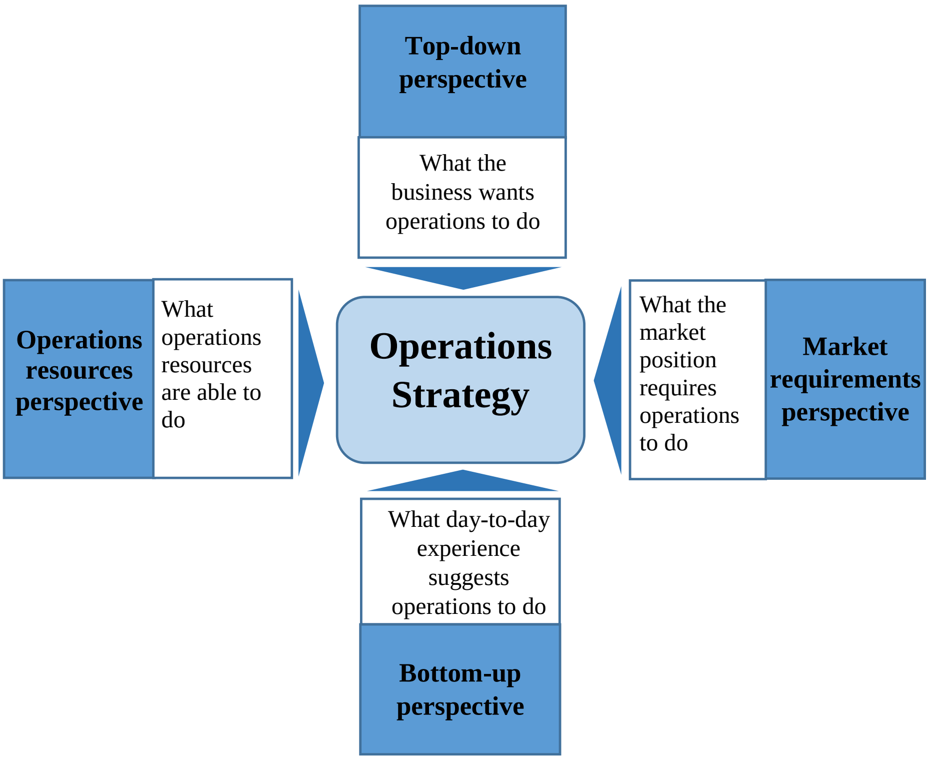

Figure 1.1: The four perspectives on operations strategy [Adapted from Slack et al. (2010)]

- Alignment
- Trade-offs
- Focus
- Forecast
- Volatility
- Flexibility

In the previous sections we briefly discussed how to design appropriate strategies based on the competitive priorities or performance dimensions/objectives. However, aligning the organisational structure and operational processes with the strategy is not an easy task, and requires a systematic approach with multiple steps to "mesh strategy with operations" (Kaplan and Norton 2008).

The first step (after the competitive strategy is designed) is to create a strategic consensus within the organisation by effective communication to employees about the strategy, objectives, and operational priorities (Boyer and McDermott 1999). Empirical research shows the influence of manufacturing executives' involvement in achieving strategic alignment is considerable (Papke-Shields and Malhotra 2001), and the coordination between manufacturing managers and general managers appears to have a significantly positive impact on the relationship between alignment and performance (Joshi et al. 2003, Tarigan 2005, Schniederjans and Cao 2009).

The next step is operationalising the strategy by making decisions in various categories such as facilities, logistics, technologies, supply chain, quality management, production and inventory planning, marketing, finance and accounting systems, etc. The main focus of the decisions is on the processes and areas that play key roles in achieving the company's competitive priorities. In other words, any decision should be in alignment with the company's main strategy. Regular strategy and operational reviews need to be set up for monitoring the progress of the implementation, continuous improvement, and, sometimes, strategy adjustment (Kaplan and Norton 2008).

One of the major decisions in operations management is supply chain strategy. As mentioned previously, it must fit with the business strategy. For instance, if flexibility is the main strategy of a firm, suppliers must be selected based on their capabilities for fast delivery and being able to quickly switch to new products. They might also need to have enough capacity to handle variations in order size, lead time, and quality level. As Kouvelis and Su (2008) outlined in their review article, when designing a global manufacturing strategy, a firm must decide on supplier selections, plant capacities, product allocations to market regions, and linking plants to market regions within the firm's global supply chain network. Moreover, there are many global factors that dominate supply chain design, for instance, fluctuating exchange rates, price uncertainties, investment financing of global facilities, regional trade agreement complexities and local content rules, international taxation complexities, and transfer pricing schemes (Kouvelis and Su 2008).

The fact that a supply chain contains a number of firms (i.e., suppliers, manufacturers, logistics providers, wholesalers/distributors, and retailers) who interact to deliver products or services for the customers (Tang 2006b) implies the importance of strategic alignment in order to effectively coordinate the operations strategies of all the firms. This alignment becomes more advantageous when we look at supply chain management from a global view because "supply chain processes that cross organisational boundaries can be more easily defined, analysed, and improved to provide companies with a sustainable competitive advantage." (Stavrulaki and Davis 2010)

There is an extensive literature on supply chain strategy. A large group of studies has worked on product-driven strategies, which are developed according to the characteristics of product, demand nature, and market requirements. The rest of this monograph will discuss ideas, frameworks, models, and findings presented in this group. A particular emphasis is placed on Fisher's (1997) framework, which is one of the first and most cited theories in the body of literature for product-driven supply chain strategies.

1.5 Supply Chain Strategy

A significant strategic challenge, which has been widely addressed in recent research, is the design of a company's supply chain to effectively align with its business model. Indeed, the thread of this issue dates back to the emergence of the "focused factory", which was Skinner's (1974) advice for US manufacturers who, he claimed, lacked a congruent manufacturing structure integrated with correct competitive objective(s). This thread was followed by many researchers, and resulted in an extensive literature. For instance, Dhalla and Yuspeh (1976) claimed that companies need a set of "marketing-communications models" that enable them to constantly monitor market conditions such as demand changes, and to take a remedial action when appropriate. Further, Hayes and Wheelwright (1979a, 1979b) suggested a "product-process matrix" to help companies link their manufacturing systems with their product and market competence as well as choosing appropriate market entrance-exit and learning curve strategies.

Further contributions to manufacturing strategy significantly influenced the operations management literature. From the emergence of the lean paradigm and mass production, which profoundly changed manufacturing systems especially in the auto industry (Ohno 1988), to the introduction of agile manufacturing, which was claimed to be the strategy for enterprises in the 21st century (Nagel and Dove 1991), the purpose was to maximise companies' expected profits by fitting supply structures with market requirements. Similarly, Hill's (1993) framework for identifying "order qualifiers-order winners" and the concept of "accurate response" (Fisher et al. 1997) are examples of guides for operations managers to achieve increased profit through an appropriate operations strategy. In addition, Fuller et al. (1993) introduced "logistically distinct business methods" as a guideline for companies to differentiate the way they serve distinct customers, because they recognised "averaging" was a conventional problem that often causes customers who need specialised products to be underserved, while customers for commodity-type products are overcharged. The issue is that since the two types of products differ in the nature of demand, they should be supplied by different manufacturing processes, which look mutually exclusive, but can be combined to create a complementary design. In this research, we address the issue from a supply chain standpoint and taking an analytical approach.

Similar contradiction exists when making sourcing and serving decisions. In the former, a company has the choice between a fast but expensive supplier (normally located onshore) and a slow but cheap supplier (normally located offshore), or a combination of both. In the latter, a supplier should decide whether to serve a group of customers who have low volume but stable demand (usually from individuals) or to respond to another group who place large but sporadic orders (usually form merchants), or jointly satisfy both demands. In either of these situations right decisions need to be made so that they align with the overall strategy of a supply chain, which itself matches product type and demand characteristics of the end customer, and also meet particular requirements of other business partners. Although the dual sourcing problem has been widely studied and received attention for sufficiently long time in research, dual serving has become a critical issue more recently, especially as the result of the emergence of many online daily deals platforms. Thus, we aim to address this issue seeking to formulate the optimal dual serving strategy.

These issues identified above are of the main focus of this research. In the remaining part of this chapter, we further discuss the motivations and objectives of the research in detail and present our findings as well as outline our contributions in the following chapters.

1.5.1 Fisher's Supply Chain Strategy Framework

Fisher (1997) looked at product-process matching issue from a supply chain perspective and introduced a framework that helps companies to design their supply chain strategies based on their product types. He classified products into two distinct groups, namely, functional and innovative products. The main attributes of the first group are long life-cycles, stable and predictable demand, and low contribution margins. Conversely, the second group have short life-cycles, volatile and unpredictable demand, and high contribution margins. Fisher (1997) believes each group needs its own supply chain strategy. The functional products require an efficient and lean supply chain with a cost reduction approach, while the innovative group call for a responsive and flexible supply chain with high delivery speed.

Campbell Soup, a producer of canned food, and Sport Obermeyer, a supplier of fashion skiwear, are examples of companies that provide the two distinctive types of products. A highly predictable demand for products that have been in the market for years allows Campbell Soup to satisfy nearly 98% of demand immediately from stocks of finished products. On the other hand, each year, Sport Obermeyer brings to the market a range of products with 95% of them being totally new, while only 5% of Campbell's products are new. Sport Obermeyer sometimes has a forecast error of 200% and may only have a few months to react to the market because the retail season is very short (Fisher et al. 1994, Fisher 1997).

Fisher's (1997) framework has been widely considered in the supply chain management literature. It has received many extensions from both conceptual and practical points of view. A number of empirical studies have explored it in different sectors and countries. A few researchers have also analysed it mathematically. The studies suggest that, despite the fact that Fisher's framework has received significant attention and support from the literature (Zhang et al. 2013), it still has some unanswered questions (Wright 2013), and perhaps lacks sufficient support (Lo and Power 2010), especially from an analytical viewpoint.

There are some key issues raised by the literature with regards to Fisher's (1997) proposition. The most common of which are 1) a need for hybrid supply chain strategies that deliver intermediate products with characteristics of both functional and innovative products; 2) insufficient dimensions for characterizing supply chains by product type; 3) some companies with product-supply chain mismatch do not necessarily underperform compared to those with matching conditions; and 4) the framework has not been thoroughly validated mathematically. In Chapter 2, we will review (in detail) all the existing evidence regarding the first three issues, and, in Chapters 3 and 4, we will address the last issue.

1.5.2 Product-driven Supply Chains

In addition to Fisher's (1997) framework, the supply chain management literature offers some other strategies to structure logistics and manufacturing processes according to product characteristics. For instance, a large group of researchers discuss and develop Naylor et al.'s (1999) idea of developing supply chains with lean, agile, or leagile approaches, whichever best match demand/market requirements. Specifically, "leagility" combines leanness and agility in a supply chain by strategically positioning the decoupling point, which is where product differentiation occurs. Moving the decoupling point closer to the customer allows efficiency to dominate the supply chain, resulting in the capability to provide a low cost output. This delay in product differentiation is also the essence of a postponement strategy (van Hoek 2001). On the other hand, positioning the decoupling point further from the end-user (closer to the main supplier), creates more capacity in the supply chain for customisation, i.e., a manufacturer may follow a make-to-order or engineer-to-order strategy (Olhager 2003). Mass customisation is another product-driven strategy that allows for both variety and volume, i.e., customised products at a mass production price, which needs a simultaneous focus on cost and pace. In the next chapter, we will review the literature of the abovementioned strategies.

Overall, the current accelerating competition in the marketplace shows that high speed and low cost are not sufficient for creating competitive supply chains, perhaps because these two factors are becoming more market qualifiers rather than market winners (Hill 1993). To achieve a sustainable competitive advantage, Lee (2004) suggests the Triple-A supply chain which has "agility", i.e., quick response to short-term changes in demand or supply, "adaptability", i.e., design adjustment to accommodate market changes, and "alignment", i.e., improvement of the entire chain. The successful practices of Wal-Mart, Amazon, Dell, and Seven-Eleven Japan confirm that Lee's (2004) theory is particularly true in this era where "it is supply chains that compete not companies" (Christopher and Towill 2001), and supply chain decisions are becoming more strategic than transactional (Niezen and Weller 2006).

1.5.3 A Motivating Example

The issue of developing an effective supply chain strategy has always been a significant concern, and is becoming more challenging due to the accelerating rate of competition in the current business environment. A very large scale example is New Zealand's strategic plan for Business Growth, especially in the export sector. In the international marketplace, New Zealand is well-known for its dairy products, meat, and logs/timber. For many years, these three groups of products have been New Zealand's top exports (in value)[2]. These are all primary products where having very low value-adding capacity is their main feature, which leads to low contribution margins. However, they are attractive to producers and traders because they usually guarantee a minimum of average demand, which in the long term is relatively high. Overall, 70 percent of all goods exported from New Zealand are primary products and 25 percent are manufactured products[3].

From an economic point of view, we might criticise this reliance on exporting low value-added products while higher value-added items could be produced making the international trade more profitable. The case of Fonterra, New Zealand's largest company and the world's largest dairy exporter, raises concerns. Fonterra exports significantly

[2] https://www.nzte.govt.nz/en/invest/statistics

[3] http://www.stats.govt.nz/browse_for_stats/snapshots-of-nz/nz-in-profile-2013/exports.aspx

more low-profit milk powder than high-profit infant formula. Moreover, according to The International Farm Comparison Network (IFCN) 2014 report, although Fonterra is the world's second largest milk processor in terms of milk intake (million tons/year), it holds 16$^{\text{th}}$ place in terms of average turnover ($/kg milk)[4]. Addressing this issue, the New Zealand government has targeted the ratio of exports to GDP to be 40% by 2025, and one of the key areas to focus on is "strengthening high-value manufacturing and service exports"[5].

The government's agenda of investing in high-value manufacturing exports may be in conflict with Fisher's framework. New Zealand is far from all its potential markets and, due to its geographical remoteness, it has low physical connectivity, making a responsive supply chain difficult to build. Furthermore, according to StatisticsNZ[6], only 0.45% of the country's enterprises have more than 100 employees and only 0.5% have between 50 and 100 employees. This means, based on the European Commission's definition[7], 93% of New Zealand businesses are micro, and usually, interested in leanness and cost efficiency. These issues make exporting innovative (high value) products a significant challenge. Thus, the question is to which direction (primary products or innovative products) investments in the country should be encouraged.

1.5.4 Dual Serving Problem

A special case of matching supply chain decisions with demand requirements is in the dual serving problem. This is when a company should make a choice between serving a set of routine individual customers who frequently demand a product (or a family of different types of a product) but in low quantities and some occasional orders placed by merchants (or sometimes wholesalers) in very large sizes. This problem is becoming more common in the retail industry. Jointly serving both is, of course, an option, but it raises the question of what the optimal settings of the serving strategy should be. This question was initially brought to our attention by a local company whose production and warehousing mostly

[4]http://www.ifcndairy.org/en/news/2014/top_20_list.php
[5]http://www.mbie.govt.nz/what-we-do/business-growth-agenda/export-markets
[6]http://www.stats.govt.nz/browse_for_stats/businesses/business_characteristics.aspx
[7]http://ec.europa.eu/growth/smes/index_en.htm

take place in China, while its market is global with its majority being in Australia and the owner lives in New Zealand. Although individual shoppers can make their purchase online through the company's website, they are sometimes (and more often recently) contacted by online daily deals platforms to order a large volume seeking a good quantity discount. Such orders (despite being lumpy) are attractive because of the substantial impact on the company's annual sales, but are difficult to manage in terms of inventory and sourcing decisions, as the lead time is not short and individual shoppers easily face stockout, which is in turn costly. The growth of the popularity of online deals is expected to cause more companies face the same challenge. Li et al. (2017) reported that US daily deals industry has grown by 332% over five years since 2008, and other research predicts that online retail sales constitute 13% of the US retails sales in 2019 (Forrester Research 2015). In this research, we will study the challenge by investigating both the right choice of serving (single or joint) and the optimal settings of the choice while evaluating two particular dual serving strategies, namely, aggregation, where demand from both customer groups is aggregated and immediately satisfied once received, and protection, where the lumpy demand is only served until stock on hand remains above a certain protection level.

1.6 Thesis Overview

In this section, we outline the research objectives of our study, the methodological approach, and the structure of this thesis.

1.6.1 Research Objectives

This monograph looks at supply chain management from a strategic point of view. The aim is to analytically explore whether and how the alignment between supply chain strategy and product/demand characteristics matters. We have a particular focus on Fisher's (1997) typology, which is arguably the most famous framework in the supply chain strategy literature. As previously discussed, despite the large attention that the framework has received from both researchers and practitioners over the last two decades, it still lacks an analytical validation. Thus, one of the objectives of this study is to provide such validation.

A deep knowledge of what previous research has reported on the framework is necessary to ensure our analysis is novel and concrete, as well as addressing the right concern(s) while conducting the validation. We begin with a comprehensive review of the literature regarding the framework and present a holistic picture of existing reflections on the framework. Creating such picture is another objective that needs to be addressed first. As part of this picture, other product-driven supply chain strategies, i.e., leanness, agility, leagility, mass customisation, and postponement, are reviewed.

While conducting our analysis of the framework validation, another objective is to expand on the literature of inventory management by incorporating product life cycle (to formulate obsolescence cost) into a continuous review model. The ultimate total cost model is minimised with respect to order quantity and lead time through both single- and bi-objective optimisation, under two separate make-to-order and make-to-stock settings of the supply chain.

Ultimately, addressing the dual serving problem, as a special case of matching supply chain decisions with demand characteristics, we aim to identify whether and in what circumstances jointly feeding both regular and lumpy demands is a right choice. Also, we seek to define the optimal settings of dual serving under the choice of strategy.

In summary, there are three specific research questions (RQ) that this study aims to answer. These questions are as follows:

1. How does the literature of supply chain reflect on Fisher's (1997) framework over the last two decades?
2. Can we provide analytical support for Fisher's (1997) framework? And, in general, how does the (right) choice of supply chain strategy change when demand/product characteristics change?
3. What will be the right choice (and the optimal settings) of strategy for the dual serving problem from the lens of demand characteristics?

1.6.2 Methodology of the Research

The methodology used in this study is mathematical modelling and optimisation. As we briefly pointed out earlier and will explain in detail later in the next chapter, most of the current findings in the literature are based on empirical analysis and, therefore, represent the context (e.g., country or industry) of the study. That is why the findings sometimes contradict each other and/or do not support the theory. Moreover, a few existing analytical works (that we discuss later) either obtain most of the results from numerical analysis, which is not regarded as a strong evidence or, despite identifying the right choice of strategy under given circumstances, do not provide an informative guide on the optimal supply chain decisions. Since we need, at least for the purpose of Research Question 2, an answer that is valid regardless of the country, industry, or parameters, mathematical methods are the best choice. Although this methodology also has its own limitations, e.g., simplifying assumptions, it still offers a greater degree of generalisability, thus, providing a rigorous, informative prescription that resolves the validation problem outlined in the second research question.

Another consideration regarding the research method is that we base our analysis on a centralised formulation of the problem because such a formulation does not exist in the pertinent literature of this study. Therefore, we start with a centralised decision model and other decentralised settings, e.g., two-stage decision models, can be the potential goal of future research.

1.6.3 Organisation of the Thesis

The organisation of this monograph and its flow of content/analysis that will address the outlined research questions are shown in Figure 1.2. A brief overview of each of the next chapters is as follows. Chapter 2 reviews the pertinent literature of both Fisher's (1997) framework and other product-driven supply chain strategies. This pursues the objective of creating a holistic picture of existing reflections on the framework. Chapter 3 develops a model and, through a mathematical optimization, describes the best supply chain strategy, incorporating multiple demand/product characteristics. This chapter also aims to achieve

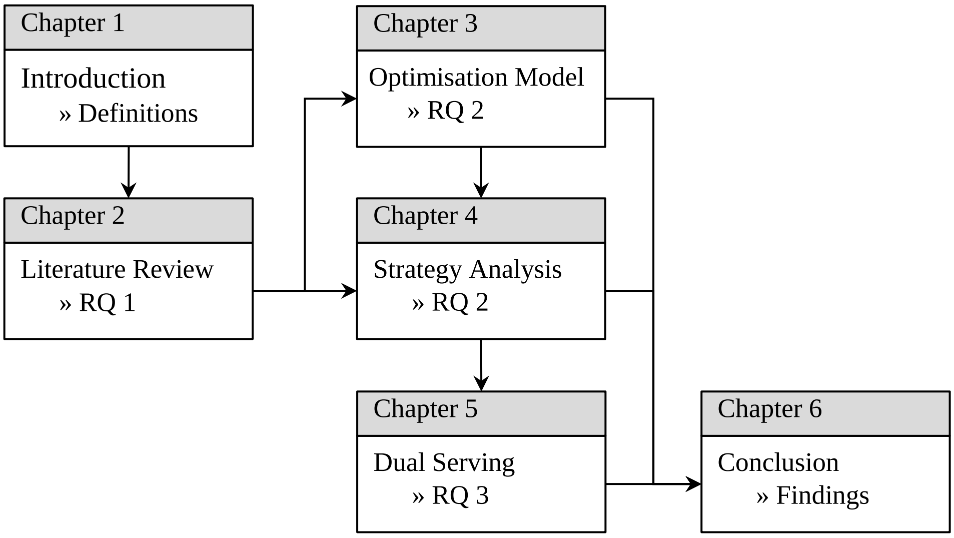

Figure 1.2: The structure of the thesis and content flow diagram

the objective of expanding on the continuous review model. Chapter 4 explores the impact of the characteristics on supply chain decisions and the alignment between them via a set of numerical analyses. It also analyses the impact when a supplier's manufacturing policy changes from make-to-order to make-to-stock via an extension to the original model. Most of this chapter discusses the validation of the framework. Chapter 5 deals with the special case of the dual sourcing problem to accomplish the the last objective outlined earlier. Chapter 6 concludes the thesis by summarizing our findings, discussing the limitations, and suggesting some interesting avenues for the future research.

Chapter 2

Literature Review

The primary focus of this research is on product-driven supply chain strategy with a particular attention to the framework that Fisher (1997) proposed. Although the framework has been widely supported, there are many studies that develop/extend it from different points of view. Further, there is some empirical evidence that challenges the adaptability of the framework, or question its capability after almost twenty years.

In this chapter, we first explain how the framework and the theory behind it work, and then review the existing studies that discuss it in their research. Finally, we look at other strategies that are developed based on the characteristics of product and demand. Key findings of the review are summarised at the end.

2.1 Fisher's Framework

A seminal work in supply chain strategy is Fisher's (1997) article in Harvard Business Review. According to Google Scholar, this article had been cited 4600 times by early 2018. The framework introduced in this article triggered a large number of further studies by both researchers and practitioners, and created a broad domain of knowledge on supply chain management. In this section[1], we look at Fisher's framework and briefly describe it by summarising key concepts leading to the design of a right supply chain strategy.

2.1.1 Functional or Innovative Product?

With regard to the nature of demand, products are classified into two main groups: functional or innovative. Demand for functional products, which usually satisfy people's

[1]The materials presented in this section come from Fisher's (1997) article, unless we cite them separately.

basic needs, is stable and predictable. Because of very slow changes over time, they have a long life cycle. In addition, the expected contribution margin for these kind of products is very low due to a large number of participants in the marketplace that compete on price. The majority of items in a grocery store or gas station are functional.

On the other hand, being new and designed based on special needs results in a volatile and unpredictable demand for innovative products. Their expected profit margin should therefore be high, but their life cycle is relatively short. What companies bring to technology or fashion apparel markets are usually innovative products. A list of key characteristics of both innovative and functional products is given in Table 2.1.

2.1.2 Efficient or Responsive Supply Chain?

A supply chain's function is classified into two different roles: physical and market mediation. The former is more visible because it is based on material and physical resources, while the latter mostly consists of information. A supply chain works well when material efficiently flows downstream from the suppliers (physical function), and information flows efficiently upstream from the market (market mediation function). Therefore, a proper combination of both functions is necessary, but the importance of each differs when the priorities of a supply chain's performance are different.

With more attention and concentration on the physical function, a company seeks to minimise cost and inventory and maximise production efficiency; this makes the supply chain "physically efficient". Conversely, a comprehensive observation of the marketplace with an efficient information exchange enables a supply chain to react quickly to changes in the demand. This brings high flexibility and agility, and as a result, makes a supply chain "market responsive". Table 2.2 compares the main characteristics of both types of supply chain.

2.1.3 Does the Supply Chain Match its Products?

Designing a physically efficient supply chain requires a minimum level of stability and predictability of demand, according to which the production plan and corresponding

Table 2.1: Functional versus innovative products [Adapted from Fisher (1997)]

Aspects of demand	**Functional products (Predictable demand)**	**Innovative products (Unpredictable demand)**
Product life cycle	More than 2 years	3 months to 1 year
Contribution margin	5% to 20%	20% to 60%
Product variety	Low (10 to 20 variants per category)	High (often millions of variants per category)
Average margin of error in the forecast at the time production is committed	10%	40% to 100%
Average stock-out rate	1% to 2%	10% to 40%
Average forced end-of season markdown as percentage of full price	0%	10% to 25%
Lead time required for made-to-order products	6 months to 1 year	1 day to 2 weeks

Table 2.2: Physically efficient versus market responsive supply chains [Adapted from Fisher (1997)]

Aspects of Supply Chain	**Physically Efficient Process**	**Market Responsive Process**
Primary purpose	Supply predictable demand efficiently at the lowest possible cost	Respond quickly to unpredictable demand in order to minimize stock outs, forced markdowns, and obsolete inventory
Manufacturing focus	Maintain high average utilization rate	Deploy excess buffer capacity
Inventory strategy	Generate high turns and minimize inventory throughout the chain	Deploy significant buffer stocks of parts or finished goods
Lead-time focus	Shorten lead time as long as it does not increase cost	Invest aggressively in ways to reduce lead time
Approach to choosing suppliers	Select primarily for cost and quality	Select primarily for speed, flexibility and quality
Product-design strategy	Maximize performance and minimize cost	Use modular design in order to postpone product differentiation for as long as possible

replenishments are scheduled. Stable relationships with suppliers and a high production volume will decrease the variable costs. Therefore, the lifetime of the product should be long enough. Necessarily, a functional product is best suited to these conditions. The market for this product will be price sensitive, so effective strategies for production efficiency and cost reduction in the supply chain are necessary to maintain a competitive advantage in the market.

On the other hand, this appears to be the wrong approach if the product is innovative. Because of uncertainty and volatility in demand, relevant information from the marketplace needs to be swiftly gathered to reflect any corresponding changes in the demand. The supply chain should respond to the market as quickly as possible. Due to the short life cycle and high profit margin for the product, competition will no longer be on price, but instead on lead time, service level, flexibility, reliability, or quality. Thus, responsiveness to customers' specific expectations (which make them willing to pay more) is the crucial characteristic of the supply chain for innovative products. Figure 2.1 displays how supply chains match products.

2.1.4 How to Design an Ideal Supply Chain?

If a company intends to ensure it has an appropriate supply chain strategy, first, managers need to indicate whether their product is functional or innovative. Table 2.1 is helpful in this step. They should then review their current supply chain conditions to determine if it is physically efficient or market responsive. Looking at Table 2.2 could guide such a decision. The next step is to figure out whether the product and the supply chain match. Figure 2.1 helps companies to find their position.

Although both the upper right hand cell and the lower left hand cell demonstrate mismatch and predict problematic conditions, we rarely see companies in the latter one, because conventionally companies have concerns about efficiency in their supply chain. However, when they decide to bring innovations to their products, usually to reap higher margins, they often neglect to restructure their supply chain accordingly. As a result, they start delivering innovative products but still with efficiency-focused supply chains. This

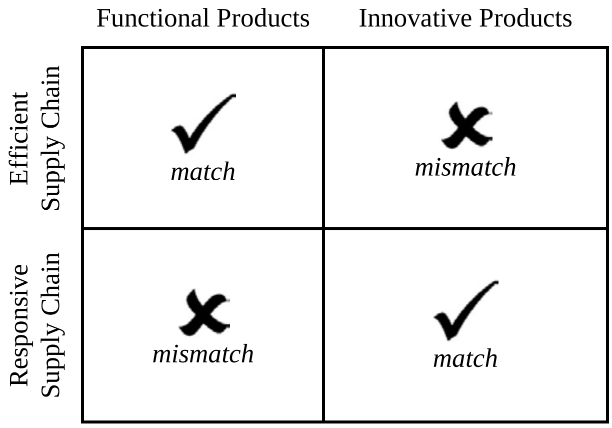

Figure 2.1: Matching supply chains and products [Adapted from Fisher (1997)]

can lead to significant opportunity costs in the chain. Some helpful tips for successfully maintaining each supply chain strategy follow.

I) *Tips to maintain a physically efficient supply of functional products*

Cost reduction and efficiency improvement are not new ideas in an operational context. There are a wide range of strategies, e.g., lean manufacturing, which companies can follow to cut total cost throughout the supply chain. However, some important points should be taken into account when the efficiency is going to support a flow of functional product to the market:

- Improving inter-organisational coordination with suppliers and distributers works better than aggressively cutting cost. The advantages of electronic networks and information systems infrastructure can be considerable in this regard.
- Keeping predictable, stable demand is better than running promotion programs in order to increase sales occasionally. The latter can result in an addiction to incentives and turns simple predictable demand into something more chaotic.
- Both cooperative and competitive models between partners of a supply chain can lead to substantial profit, because of strong sales of a functional product. However,

using both models at the same time with a partner is not sensible, as they require fundamentally different behaviors.

II) *Tips to maintain a responsive supply of innovative products*

Dealing with uncertainty in demand is the main issue for innovative products. Companies should first accept this uncertainty as intrinsic to their products and then aim to capture the opportunity of a high profit margin by designing a responsive supply. Some coordinated strategies that can be employed to cope with uncertainty include

- Using market mediation models to reduce uncertainty by continuous observation of demand.
- Cutting lead time and increasing the flexibility of the supply chain to mitigate uncertainty. The final configuration could be processed at a point when demand is as accurate as possible.
- Planning for levels of buffers of inventory or spare capacity of resources that are able to react to the remaining residual uncertainty.
- Mass customisation is a strategy that allows the company to quickly deliver a variety of products in high volume and close to mass-production prices. This strategy combines the concepts of efficiency and responsiveness, but does not work for all companies and also has its own challenges (see Section 2.3).

2.2 Literature Regarding Fisher's Framework

In this section, we review a number of studies that have specifically focused on Fisher's framework. The studies followed three main approaches. A few of them discussed the framework from a technical viewpoint and developed it conceptually. A larger group of researchers analysed the framework empirically based on either an individual company case study or a survey. The third group consists of a small number of papers that used mathematical modelling methods. The following subsections explore the contribution of the three groups separately.

2.2.1 Conceptual Development

Almost at the same time of Fisher's (1997) article publication, Lamming et al. (2000) carried out an interview-based survey among 16 European firms of various industry sectors in 1997 to identify how companies design and establish their supply networks. Although their primary purpose was not specifically testing Fisher's framework, they reported a good conformance between the survey findings and the framework. Moreover, the study indicated that product "uniqueness" and "complexity" are two additional factors that firms apply in supply network configuration, thus should be considered in product type characterisation. Table 2.3 displays how four distinct types of supply networks can be derived based on the degree of product complexity and innovation-uniqueness. Particularly, the number of components, subassemblies, structure of bill of materials (BOM), and level of technology change according to product complexity and consequently affect the supply chain design (Catalan and Kotzab 2003, Cigolini et al. 2004).

Another factor that affects supply chain strategy is the level of stability in processes and technologies involved throughout a company's supply chain. Lee (2002) believes when the structure and mechanisms used in a supply chain is still "evolving", a higher level of uncertainty is expected compared to when we have a network of mature and well-established processes that forms a "stable" supply chain. With a number of successful examples, Lee (2002) suggested some practical methods for uncertainty reduction in both supply and demand. Information sharing and collaborative replenishment are crucial for reducing demand uncertainty. Free exchanges of information over the product life cycle, early (product) design collaboration, and supplier hubs are effective ways for taming uncertainties in the supply chain. Particularly, taking advantage of the Internet allows companies to develop an appropriately aligned supply chain strategy with product uncertainties based on the framework displayed in Figure 2.2. Lee (2002) extended Fisher's taxonomy with the following strategies:

- Efficient supply chain—maximising cost efficiency
- Responsive supply chain—maximising flexibility and responsiveness to the customers' needs

Table 2.3: Revised classification of supply networks [Adapted from Lamming et al. (2000)]

Supply chain characteristics		Product uniqueness	
		High (innovative)	Low (functional)
Product complexity	High	*Competitive priority:* speed and flexibility, innovation, quality, supremacy *Sharing of resources and information:* large amounts of non-strategic information enabled by IT – problematic when involving sensitive information and knowledge	*Competitive priority:* cost reduction, quality sustainability, service *Sharing of resources and information:* large amounts of non-strategic information enabled by IT – generally unproblematic: may include cost breakdowns and strategic knowledge
Product complexity	Low	*Competitive priority:* speed and flexibility, innovation, quality, supremacy *Sharing of resources and information:* problematic exchange of sensitive information and knowledge – IT less critical	*Competitive priority:* cost (by high volume production), service *Sharing of resources and information:* generally unproblematic – may include cost and strategic knowledge – IT less critical

		Demand uncertainty	
		Low (Functional products)	High (Innovative products)
Supply uncertainty	Low (Stable processes)	*Efficient supply chains*	*Responsive supply chain*
Supply uncertainty	High (Evolving processes)	*Risk-hedging supply chains*	*Agile supply chains*

Figure 2.2: Aligned strategies (Lee 2002)

- Risk-hedging supply chain—Sharing risks in supply disruptions by sharing and pooling resources
- Agile supply chain—Responding flexibly to the customers' needs, while hedging supply risks of shortages and disruptions by pooling capacity of inventory and other resources

An empirical study of 243 leading manufacturers in Taiwan shows a significant improvement in the performance of firms that have aligned their supply chain strategy with product uncertainties (Sun et al. 2009). The study tested and supported Lee's (2002) framework by using a profile deviation approach in a survey. In addition, they found a range of variables, namely price, flexibility, quality, delivery, service, operational support systems, market information systems, inter-organisational systems, and strategic decision support systems, that contribute to supply chain design success by integrating manufacturing and information systems capabilities.

Uncertainties in supply and demand, have also been addressed in a variety of research in the supply chain modelling literature. The two major strategies that have been particularly discussed are mix flexibility (to deal with demand uncertainty) and dual sourcing (to cope with supply uncertainty) (Vakharia and Yenipazarli 2008). Bridging the two strategies, Tomlin and Wang (2005) formulated four different network structures, namely, single-source dedicated, single-source flexible, dual-source dedicated, and dual-source flexible, and showed which structure works best in which configuration of uncertainty factors, i.e., demand, price, investment risks, contribution margin, supplier's reliability, and risk tolerance. According to Tomlin (2006, 2009), who investigated supply-side and demand-side disruption management tactics in the context of a firm that sells multiple products with short life cycles and long lead times, the ordering of strategies in terms of effectiveness of dealing with disruptions is: contingent sourcing; dual sourcing; and demand switching. Ray et al. (2005) analysed the role of price-driven uncertainties in the demand side by modelling the incorporation of price sensitivity into Lee's (2002) framework in two alternative supply chain management paradigms, centralized and decentralised. They showed how optimal decisions on pricing and stocking, as well as profitability, are affected by price sensitivity, demand uncertainty, and delivery time variability.

Stavrulaki and Davis (2010) claimed that, despite the inclusion of supply uncertainty in Lee's (2002) framework, it is not yet explicitly defined which production and logistics processes best suit each supply chain type. Addressing this issue, and taking into account the "product-process matrix" of Hayes and Wheelwright (1984), they extended the "supply chain product process matrix" of Lummus et al. (2006) to create a new framework that aligns products with supply chain processes and strategy. As displayed in Figure 2.3,

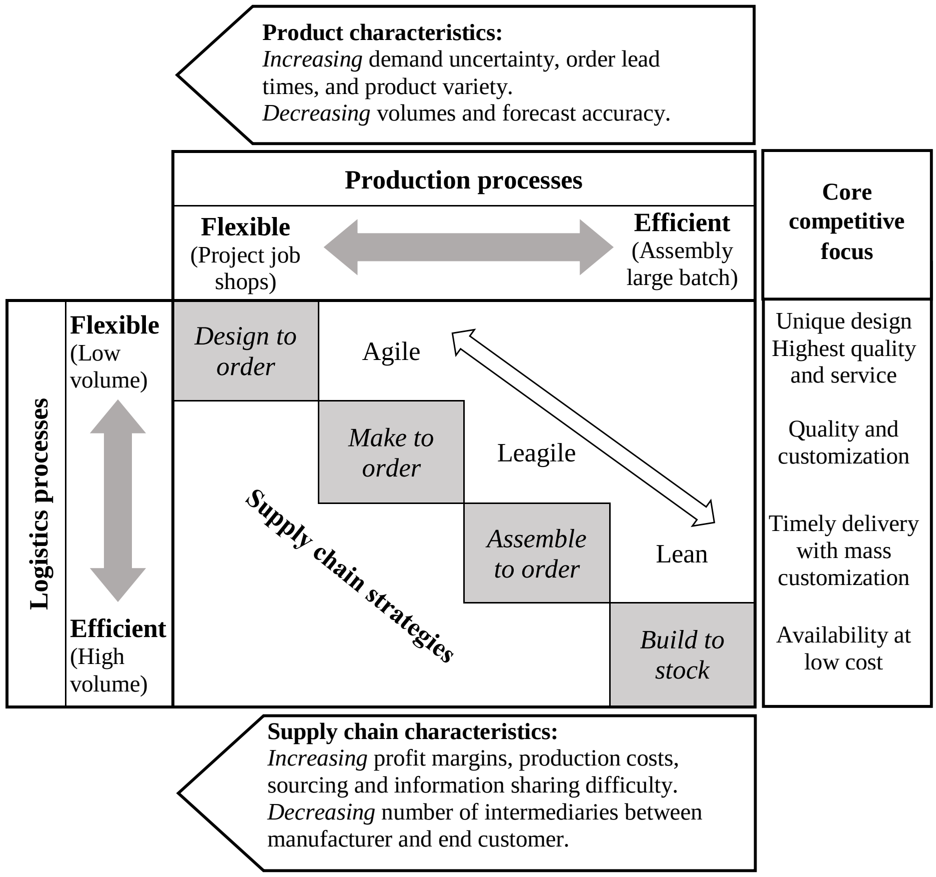

Figure 2.3: Aligning products with supply chain processes and strategy [Adapted from Stavrulaki and Davis (2010)]

the framework illustrates the most appropriate production and logistics processes for different product characteristics and matching supply chain strategies that also fit with the company's core competitive priorities. Build to stock (BTS), assemble to order (ATO), make to order (MTO), and design to order (DTO) are the four supply chain configurations that vary from lean to leagile and to agile.

Extending the main concept of Fisher's framework to a green context, Youn et al. (2012) explored whether and how eco-efficient supply chains (EESC) and eco-responsive supply chains (ERSC) can be established, and if they really differ from each other. They drew a comparison between two different companies with environmentally friendly businesses models, and discovered that each company follows different approaches in operations management. For instance, production process improvement received the main investment (to achieve environmental excellence) in one company, while product design innovation (to offer environmentally friendly features) was the primary focus in another company. From a supply chain perspective, EESC should mostly work on process innovation/improvement, and ERSC should focus on product innovation, supplier collaboration, and consumer education.

Reverse supply chain design is another area that Fisher's taxonomy has been drawn to for the purpose of maximising the total value captured from product returns. Blackburn et al. (2004) defined this value based on the amount of time it takes for a returned product to be retrieved; thus, the product is characterised by the marginal value of time (MVT). They used MVT as a measure of product type to create the appropriate reverse supply chain design. The positioning of the evaluation activity (to determine the condition of the product) defines whether the reverse supply chain should be efficient (for low MVT products) by centralising the activity, or should be responsive (for high MVT products) by decentralising the activity. Moreover, adopting delayed product differentiation, which is known as "postponement", in the former helps with minimising processing costs, while early differentiation, which is called "preponement", in the latter leads to minimising delay costs. The expected length of product life cycle is another factor in reverse supply chain design, which, according to Guide et al. (2006), should be based on a trade-off between efficiency (to be maximised for long product life cycles) and cycle time (to be minimised for short product life cycles).

2.2.2 Empirical Analysis

In terms of quantitative analysis, we found two different groups of empirical studies. The first group consists of two papers that have focused on individual companies to investigate the impact of supply chain alignment with product type. Another group of papers has conducted survey-based quantitative analysis, which tests Fisher's framework among many companies in different countries. In the following, we review the two groups.

I) *Individual-case studies*

In an electronics and telecommunication company, Payne and Peters (2004) defined three possible supply chain models for the company: dispersed stock, central stock, and finish to order. Products were clustered based on seven attributes: volume, volatility, order line value, frequency of order lines, order line weight, substitutability of a product, and number of customers buying each product. With a set of specific thresholds for the attributes, a matrix of 'which cluster best suits to which supply chain model' is attainable to assign an appropriate supply chain model to each product. A simulation analysis of the company's business conditions after application of the realignment scenario showed a potential for significant improvement in both financial and operational levels. For instance, the realignment recommended less reliance on the traditional dispersed stock model (and more use of the central stock) resulting in a reduction of 32% in total supply chain costs and a reduction of 22% in inventory investment. The simulation of this product segmentation and supply chain alignment also illustrated a considerable improvement in order lines, lead times, and safety stock. Overall, the study revealed a high value, when a supply chain matches with the product type, but a high cost when they mismatch.

Another study was carried out in a toy manufacturer with seasonal and volatile demand. Wong et al. (2006) chose four determinants, i.e., forecast uncertainty, demand variability, contribution margin, and delivery time, for product differentiation, and three strategies, i.e., physically efficient, physically responsive, and market responsive, for supply chain configuration. Their extended framework describes how for certain thresholds of determinants, each strategy is suitable and, therefore, which manufacturing process of make to order (MTO), make to stock (MTS), and assemble to order (ATO) can be most helpful. A collection of 18 months of data (2002/3) from 667 toy products was used for the analysis. The framework indicated that, overall, the toy company needed 37% physically responsive and 58% market responsive supply chains. In addition, the study identified three new types of products. "Intermediate" products have characteristics between the functional and innovative types and hence are best suited to a physically responsive strategy, which was already suggested by Li and O'Brien (2001). "Dream" and "suicide" products are those "with a low forecast uncertainty and yet high contribution margin" and "with high forecast uncertainty but low contribution margin", respectively. Having a responsive supply chain strategy recognised as appropriate for toy products (that seem to be more innovative than functional items) provides supporting evidence for Fisher's framework. However, the need for new additional product classes and supply chain strategies shows the framework has some potential for extension. One possible extension is shown in Figure 2.4 when products are clustered based on forecast uncertainty and contribution margin.

II) *Survey-base studies*

The level of product variety is a factor that helps differentiate between types of products. Randall and Ulrich (2001) studied the correlation between product variety and supply chain structure, and the possible results of alignment between them. Their empirical analysis on the North American mountain bike industry revealed that firms which design their supply chain strategy according to the variety of their products enjoy a better performance compared to firms that fail to match them. Based on the data set of this study, Randall et al. (2003) then empirically tested Fisher's framework. They measured the impact of market growth rate, product contribution margin, product variety, and uncertainty in both demand and technology on the likelihood of choosing efficient or responsive strategy when firms decide to enter the market. The location (overseas or local) of production plants with respect to the target market (North America) was selected as a proxy for supply chain strategy (efficient or responsive). Their statistical analysis discovered an association between higher growth rate and an efficient supply chain choice, while a lower rate associates with a responsive option. Also, supplying products with more variety or higher contribution margin requires a more responsive supply chain to enter the market.

Theoretically, the possibility of reducing obsolescence risk, stock-out risk, and inventory investment by using short replenishment lead times helps a responsive firm cope with demand and technological uncertainties more effectively, compared to efficiency-focused firms that are less flexible. However, Silver et al. (1998a) reported no significant difference in either demand or technological uncertainties for choosing responsive versus efficient supply

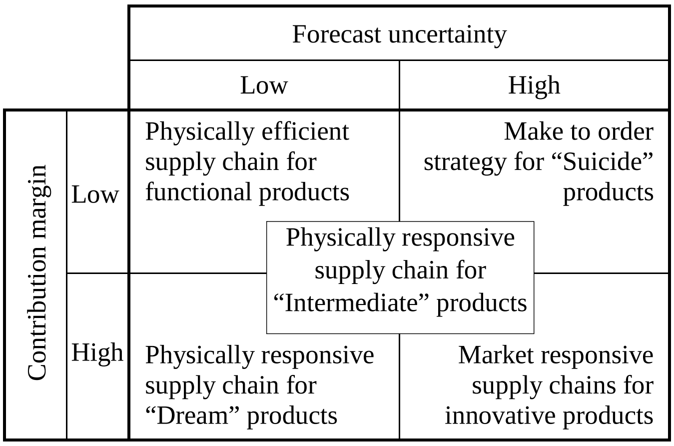

Figure 2.4: Extension of Fisher’s framework for volatile supply chains [Adapted from Wong et al. (2006)]

chains. But, this result contradicts what Sun et al. (2009) found, namely that a significant conformance exists between environmental uncertainty and supply chain responsiveness. Clearly, there is a need for more research in this area.

The reflection of Fisher’s taxonomy of supply chain strategies was not detected in companies’ strategic decisions in Sweden. Selldin and Olhager (2007) carried out a mail survey study among 128 Swedish manufacturing plants. They aimed to measure the degree to which companies establish supply chain strategies that fit to their products (based on Fisher’s framework), and if this fitness improves their performance. Table 2.4 shows more details of their factor analysis. Although they found more companies in matching conditions, there were a large number of plants still in the mismatch. Table 2.5 summarises the degree of support that the results of this study gave to the initial hypotheses. The authors concluded “a match between products and supply chains does not necessarily mean higher performance than companies with mismatches.

Similarly, Qi et al. (2009) found a group of Chinese companies that were operating in the marketplace by using their own traditional supply chains, where a primary focus was placed on neither lean nor agile strategies while they had either functional or innovative products. However, the companies with matching supply chain strategy showed a better

Table 2.4: Metrics used for survey analysis [Adapted from Selldin and Olhager (2007)]

Factors for product type	**Factors for supply chain design**	**Factors for company's performance**
- Product life cycle - Lead time required - Product variety - Average margin of forecast error - Average stock-out rate - Contribution margin	- Minimize cost - Minimize inventory - High average utilization rate - Cost-restricted lead-time reduction - Excess buffer capacity - Significant buffer stocks - Quick response - Aggressive lead-time reduction	- Cost - Product quality - Delivery speed - Delivery dependability - Volume flexibility - Product mix flexibility - Profitability

Table 2.5: Survey results [Adapted from Selldin and Olhager (2007)]

Hypotheses for fitness	Result	Hypotheses for performance	Result
H1a: Companies with functional products choose a physically efficient supply chain as opposed to a market-responsive supply chain	Supported	H2a: Companies with functional products in physically efficient supply chains perform better on cost.	Not supported
H1b: Companies with innovative products choose a market-responsive supply chain as opposed to a physically efficient supply chain.	Not supported	H2b: There is no performance difference in terms of product quality.	Cannot be rejected
H1c: Companies with a physically efficient supply chain use it for functional products as opposed to innovative products.	Supported	H2c: Companies with innovative products in market-responsive supply chains perform better on delivery speed and flexibility.	Not supported
H1d: Companies with a market-responsive supply chain use it for innovative products as opposed to functional products.	Not Supported	H2d: Companies with matches between products and supply chain perform better on delivery dependability.	Partially supported
		H2e: Companies with a match between product type and supply chain type have higher profitability than companies with a mismatch.	Not supported

performance in both financial and operational levels. In particular, the combined lean and agile strategy performs better than the others (lean or agile) from a customer service view, but lean strategy is the best in terms of operating costs. Since these better performing companies had their supply chain strategies well conformed to their product types, this study shows a relatively good support for Fisher's framework. Table 2.6 illustrates how they characterised supply chain strategies, product types, and firms' performance.

Although there is not a big difference between Tables 2.4 and 2.6, the results of the previous two studies differ. However, the case of using efficient supply chain for functional products is proven by both studies. Moreover, the majority of mismatches in Selldin and Olhager's (2007) study were found in the upper right hand cell of the framework. This phenomenon was predicted by Fisher (1997) because conventionally companies try to minimise their total costs to reap more profit, but when higher contribution margin of innovative products tempts them to change their products (to innovative), they usually ignore to change their business priorities (e.g., to fast delivery) too. We think this also highlights the significantly different organisation culture and management style that exist in companies that deliver functional products to those who deliver innovative products. The former group are more conservative to change and reluctant to experience new managerial practices or developments due to the potential costs that might be consequently imposed. On the other hand, the latter group are more dynamic with higher intention of practising tools that might improve flexibility and service level. Interestingly, Ramdas and Spekman (2000) reported that revenue enhancement practices are used to a greater extent by high performers among innovative-product supply chains than by high performers among functional-product supply chains.

A quantitative analysis of the US bicycle industry validates Fisher's framework. Harris et al. (2010) utilised the data published in Bicycle Retailer and Industry News in 2006 to select a group of five models of bicycles as functional and another group of five as innovative. The selection was based on three variables, i.e., forecast margin error, contribution margin, and stock-out rate. The models' names range from A to J with A and J being pure functional and pure innovative models, respectively. Also, both efficient and responsive

Table 2.6: Items used for factor analysis [Adapted from Qi et al. (2009)]

Supply chain strategy	**Organization performance**	**Product characteristics**
Lean - Product standardization - Waste reduction - Cost reduction - A few long-term suppliers - Low cost, high quality suppliers - Seldom supply chain structure changes	*Operational* - Unit manufacturing cost - Inventory turnover - Overall labor productivity - Stock-out cost - Obsolescence cost - Overall product quality - Customer service level - Pre-sale customer service - Responsiveness to customers - Delivery speed - Delivery dependability - Volume flexibility - Product mix flexibility - New product flexibility	- Demand variability - New product's time-to-market - Finished product volume - Introduction interval of new products
Agile - Demand volatility - Quick response to the market - Buffer capacity - Product personalization - Flexible and fast suppliers - Many short-term suppliers - Frequent supply chain structure changes	*Financial* - Return on investment (ROI) - Return on sale (ROS) - Market share - Growth in ROI - Growth in ROS - Growth in market share	

configurations of a potential supply chain were modeled to be measured by gross profit per unit (of product). A multi-echelon inventory optimisation program, called Inventory Analyst^{TM}, simulated 20 possible scenarios in which each bicycle model is assumed to be supplied by both supply chains. Figure 2.5 illustrates the performance of all scenarios. Clearly, in the chart, when products change from pure functional (A) to pure innovative (J), the preferred supply chain (with higher gross profit) changes from efficient to responsive accordingly. Furthermore, the supply chain performance difference is larger for innovative products than for functional products. The authors' interpretation of this phenomenon is that choosing a wrong supply chain is more likely to be apparent (and perhaps detectable faster) for innovative products compared to functional products, for which, in reverse, the consequences of selecting a responsive supply are modest in the early stages.

Another noticeable observation from Figure 2.5 is the area (called the Hybrid Solution Space) in which one functional product (E) along with two innovative products (F, G)

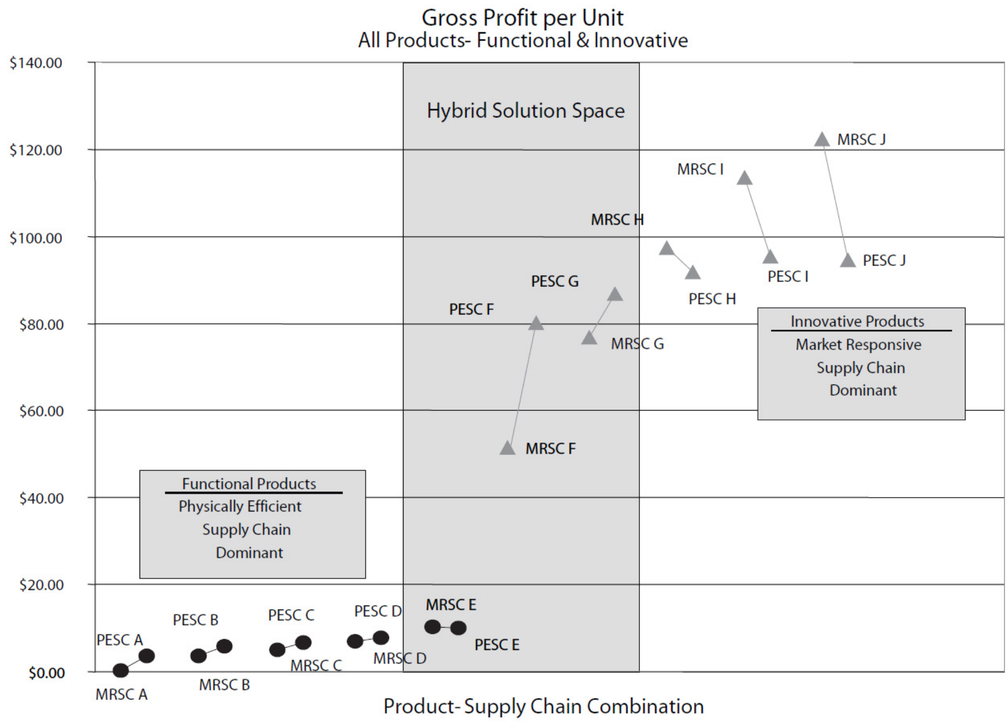

Figure 2.5: Gross profit per unit of product [PESC: physically efficient supply chain, MRSC: market responsive supply chain] (Harris et al. 2010, p. 39, reproduced with permission)

show nonconformity. More investigations on this revealed that when the attributes of a functional products are fading (e.g., by growing stock-out rate), the market responsive strategy may be preferable at some stages when the higher product availability that this strategy provides outweighs slightly the higher cost per unit that is required to make the product. Likewise, the considerable cost reduction provided by physically efficient strategy may worth more than product availability given by market responsive strategy, when an innovative product is showing more stability in the market. This Hybrid Solution Space reminds us of the intermediate product (Wong et al. 2006) that calls for a physically responsive supply chain strategy (Li and O'Brien 2001). It also could be another support to the idea of creating a supply chain frontier, which describes a successful combination of both efficiency and responsiveness, and will lead a company to perform more profitably than competitors (Selldin and Olhager 2007).

Table 2.7: Results of a survey among 107 Australian manufacturers [Adapted from Lo and Power (2010)]

Hypothesis	Result
H1: The association between product nature and supply chain strategy is significant.	Rejected
H2: Firms providing functional products emphasize efficiency-related strategies more than firms providing innovative products.	Rejected
H3: Firms providing innovative products emphasize responsiveness-related strategies more than firms providing functional products.	Rejected

A study among 107 Australian manufacturers challenged Fisher's framework in a different way and questioned its validity for today's business conditions. Lo and Power (2010) designed a survey-based questionnaire to test the framework based on three specific hypotheses that are listed in Table 2.7. The first issue that the results highlighted was the lack of any significant relationship between product type and supply chain strategy. Secondly, none of the efficient and responsive strategies appears to be emphasised by firms, irrespective of the type of product they deliver. Overall, more than 70% of respondents indicated that they deliver a mixture of both functional and innovative products and also efficiency and responsiveness are not mutually exclusive in their organisation. The authors argued that there are four reasons why this framework does not receive any support from their results:

1. There are issues in the way Fisher split products into two distinct mutually exclusive types (of functional and innovative).
2. Firms appear to consider more factors in choosing a supply chain strategy than described by Fisher.
3. Characteristics of supply chain strategies proposed by Fisher have changed over the past decade.
4. A hybrid strategy, which employs both efficiency and responsiveness, is adopted by businesses in reality.

With regard to Lo and Power's (2010) results, we have some evidence in the literature that identifies a class of products with attributes of both a standard and an innovative types (Huang et al. 2002, Wong et al. 2006, Harris et al. 2010). In addition, there are studies that indicate the need for hybrid strategies (Christopher and Towill 2002, Harris et al. 2010, Huang 2013, Li and O'Brien 2001, Naylor et al. 1999). However, they all agree that a supply chain strategy should fundamentally fit the nature of demand and market requirements that are both dependent on the type of product.

Interestingly, in a recent study in Romania, companies have shown a significant intention to design their supply chains in alignment with their product type even though the study reported that the alignment did not necessarily improve a company's performance. According to Wright's (2013) investigation among 418 Romanian manufacturers, companies with innovative products have more probability to follow a responsive supply chain strategy than to follow an efficient strategy. Furthermore, the size (of company) and the position (in the supply chain) are other factors that influence the strategy: the larger or the further upstream a company is, the more likely it will have a responsive strategy. To explain why supply chain and product type alignment did not show any positive impact on the companies' performance, one possible interpretation is that the level of competitiveness was not high enough to make consequences of a mismatch noticeable. Another possibility could be the fact that the financial status (for a limited period of time) is not comprehensive enough to compare a company's overall performance.

Conversely, a survey of 259 US and European manufacturers shows that the return on assets of a firm increases when the degree of supply chain fit (defined as the match between supply and demand uncertainty of products and supply chain responsiveness) improves (Wagner et al. 2012). This study also reports that firms with "negative misfit" (i.e., having a responsive strategy for functional products - positioning at the bottom left cell of Figure 2.1) have a lower financial performance than those with "positive misfit" (i.e., having an efficient strategy for innovative products - positioning at the top right cell of Figure 2.1). In other words, overinvesting in unnecessary responsiveness is rather less desirable than investing into measures to increase efficiency, because the resulting positive misfit will more likely lead to higher return of assets than a potential negative misfit.

As far as designing an effective hybrid supply chain strategy is concerned, one possible objective could be making a trade-off between efficiency and responsiveness. The expectation in this case would be a predominantly cost reduction emphasis on the supply chain when the product has more attributes that are functional. On the other hand, lead time reduction, for instance, would outweigh cost reduction when demand calls for mostly innovative products. Zhang et al. (2013) developed a bi-objective optimisation model to find the optimal geographical locations of a dispersed manufacturing system. The objective in this model was to minimise both cost and lead time. A sensitivity analysis on the case study of a Chinese manufacturer monitored how the preferred locations for each manufacturing step (i.e., component, subassembly, and end product) changed based on the levels of demand variability (i.e., unseasonal, seasonal, and fashionable). Accordingly, supply chain requirements changed from efficient (when a cost-sensitive product, unseasonal, is manufactured) to responsive (when a time-sensitive product, seasonal or fashionable, is manufactured). This study proves a strong association between supply chain strategy and product type, but suggests a hybrid, efficient-responsive, objective as many companies intend to offer both functional and innovative products.

2.2.3 Mathematical Analysis

The first and most straightforward study that mathematically examined Fisher's framework with a modelling approach, was done by Li and O'Brien (2001). In this multi-objective optimisation model, demand uncertainty (in both finished product and raw materials) and value-adding capacity characterise the product type. Profit, responsiveness, and reliability were used as three criteria to measure the performance of a supply chain by means of a weighted function of expected total cost, expected lead time, and expected delivery delay. Based on a sensitivity analysis, a market responsive supply chain is the best choice when demand uncertainties and product value-adding capacity are in high levels (showing support for Fisher's framework). However, a physically efficient strategy appears unsuitable for functional products that have low level of demand uncertainty and value-adding capacity (showing a contradiction to Fisher's framework). Instead, a physically responsive strategy, which is devised by the authors to represent a manufacture to stock (MTS) system, outperforms other strategies when the product is functional. As only two factors have been considered in product characterisation, further extensions are required to model the framework more realistically. Moreover, the manufacturing to order (MTO) system is selected as a physically efficient strategy in this study, while we normally use MTO when demand is volatile and high levels of customisation and flexibility are required (Holweg and Pil 2001). So, it seems the authors have considered a different definition for modelling an efficient strategy compared to what Fisher has described in his article.

The second study with a modelling approach is Langenberg et al.'s (2012) mathematical optimisation model, which is aimed at indicating whether, how, and how much the alignment between product and supply chain portfolios can help a firm save cost. In this model, products are characterised primarily by cost, demand, and lead time metrics. The cost includes holding, stockout, order setup, and product-specific procurement costs. Demand is formulated as a continuous distribution with specific mean and standard deviation. The lead time is for production and assembly operations, thus differs from the lead time in the supply chain. Moreover, total lead time and associated costs are used to set the degree of physical efficiency or market responsiveness in a supply chain. With an objective function of minimising the total cost of product delivery and supply chain portfolio complexity, they examined two main scenarios, namely, a single product and a mix of products. The results in the single product environment confirm that a higher level of responsiveness is required to supply innovative products compared to functional products (a support to Fisher's idea).

Further support for Fisher's framework is attained in this study when a portfolio of innovative products versus a portfolio of functional products is considered. In the former case, a set of market-responsive supply chains are required, while in the second case a set of physically efficient supply chains is used. However, the degree of diversity in the product portfolio changes the variety of chains required, so that more homogeneity in products results in a tighter supply chain portfolio. As a result, splitting supply chain strategies into either market-responsive or physically efficient (as Fisher suggests) looks insufficient. Furthermore, the optimally-aligned chain with particular products could change from one set of (market responsive) supply chains to another (functional set). Cost saving is obvious when supply chain design has an optimal alignment with product type, though the level of saving varies. The savings are significant when a homogeneous product portfolio is optimally assigned to a single supply chain. However, it is more sensitive compared to when a heterogeneous portfolio is in use, because some products might be better off with a non-optimal supply chain design.

2.2.4 Broader Models and Implications

We found a number of studies that contribute to product-driven supply chain strategy and particularly referred to Fisher's taxonomy/segmentation but did not aim at developing or examining his framework. These studies usually introduce their research questions by referencing Fisher's article as a theoretical basis for their discussion. For instance, the importance of both cost and lead time management was a conclusion that Zhang et al. (2013) drew on Fisher's framework, and developed their bi-objective optimisation model of supply chain design for dispersed manufacturing. The optimal geographical locations that the model offered for manufacturing plants in a study in China made a trade-off between efficiency and responsiveness. The locations turned out to change accordingly i.e., from far and cheap to close and expensive, when the characteristics of products changed i.e., from functional to innovative.

The impact of competition on a firm's choice between efficiency and responsiveness was studied by Wang et al. (2014) through incorporating another dimension, competition, into Fisher's framework. They analytically demonstrated how the relative magnitudes of the value of commitment and the value of market information jointly determine the strategic choice. Their primary model suggests that less intense competition (which has resulted from product innovation) is complementary with responsive production. Also, analysis of the extended model shows that, in a competitive environment, greater operational flexibility can make responsiveness a less attractive choice, indicating a negative correlation between the power of commitment and operational flexibility.

Milner and Kouvelis (2005) slightly changed Fisher's product classifications based on the potential types of demand scheme evolution over product lifecycle, and argued that innovative products could have either a "fashion-driven" or an "evolving" demand. They explored how flexibility (in production quantity and time scheduling) enhances supply chains with different demand characteristics. The corresponding distribution of demand for functional, fashion-driven innovative, and demand-evolving innovative products were modeled by Normal, Bayesian, and Martingale processes, respectively. They observed that quantity flexibility adds the highest value to the supply chain for fashion-driven innovative products, while the highest value of timing flexibility is for a supply chain of functional products.

Morita et al. (2015) carried out a review of the best performing companies and empirically validated that not only matching product characteristics with supply processes helps the companies to create value for their customers, but also maintaining this match in the long-term is necessary. A practical way to maintain a long-term product-supply chain match is to apply the concept of an absolute supply chain orientation strategy. This strategy focuses on simultaneous strengthening of four supply chain strategy initiatives, i.e., shortening lead time, enhancing just-in-time control, improving quality, and stabilising demand.

Another application of Fisher's framework is from the apparel industry, where with a case study in North America, Stratton and Warburton (2003) explored how the two decision tools, theory of constraints (TOC) and the theory of inventive problem solving (TRIZ), can be combined to help with developing integrated efficient and responsive supply chains. Fisher's framework was adopted as the foundation of their discussion and a more emphasis was placed on the role of inventory and capacity to resolve potential conflicts/ambiguity between the integration of leanness and agility. Nevertheless, Lam and Postle (2006) believe that the apparel and textile industry has its problems with supply chain development. Short product cycle for fashion articles, long production lead time, and forecasting errors for fashion items are typical problems, and Hong Kong companies face additional challenges such as long distance from customers in the US and European markets, minimum batch sizes, and the elimination of quota restrictions in the US market. Therefore, the implications of Fisher's framework could help companies cope with the problems and challenges by developing a correct strategy and defining their position in the global supply chain of the apparel and textile industry.

Supply chain coordination from the perspective of product modularisation was discussed in some studies, which also adopted Fisher's taxonomy for product-supply chain categorization. A common result is that not only is supply chain design highly affected by the product design and level of modularisation, but also, the more innovativeness and variety the product design has, the more flexibility the supply chain configuration should have (Lau and Yam 2005, Pero et al. 2010)

If the modularity is included in the firm's processes as well, and linked to its supply chain integration strategy, the improvement of delivery performance is proven to be significant (Droge et al. 2012). In principle, modular supply chains with heavy outsourcing and many suppliers for each component are allocated to modular products, whereas integral supply chains with heavy insourcing and vertically integrated industry are developed for integral products (Fine 2000). The costs and benefits (and risks) of outsourcing of product design/development together with the impact on the supply chain configuration were reviewed by Tsay (2013) who believes "supply chains can be 'mix and match' only to the extent that the product components (and the associated business processes and IT platforms) are 'plug and play' ". Ferguson (2009) reported that product design also has a significant impact on strategic decisions in closed-loop supply chains. He explains that a firm's potential profitability of product take-back for recycling or remanufacturing, is influenced enormously by the product design.

Integrating a firm's plans for product design, manufacturing processes, and supply chain structure was studied by some researchers (Forza et al. 2005, Rungtusanatham and Forza 2005, McKay and de Pennington 2001, Ellram et al. 2007). The main purpose is to explore the interactions/interrelationships among product, process, and supply chain decisions, and develop competitive strategies by aligning the decisions. The three-dimensional concurrent engineering (3DCE) approach, whose origin turns back to Cohen and Fine (1998), was employed in a multiple case study discussion by Marsillac and Roh (2014) who created a framework that shows how product, process, and supply chain can effectively interact. Product design changes were reported to considerably affect processes and supply chain design depending on the type of product (functional or innovative), size and scope of the changes, industrial environment (competitive, fast, or flexible), and the association between the product type and supply chain characteristics.

2.3 Other Product-driven Supply Chain Strategies

The concept of structuring a supply chain in alignment with the product type, demand characteristics, and market requirements has been developed from a wide range of perspectives, leading to various strategies. Although the strategies vary in their names (and terminology used), they sometimes work similarly or have complementary roles. The previous section discussed the two primary supply chain strategies of efficiency and responsiveness, and how they match with specific characteristics of demand. In this section, we review some more strategies, namely, leanness, agility, leagility, mass customisation, and postponement. For each strategy, we briefly describe its history and origin, key concepts and elements, as well as corresponding conditions for supply chain implementation. The review provides a more holistic picture of the product-driven supply chain literature, how it historically backs Fisher's proposition, and the extent to which it technically supports/develops his framework in various ways and different terminology. For instance, lean production and agile manufacturing fundamentally aim to achieve efficiency and responsiveness, respectively, and therefore, their literature should be studied for more constructive guidelines on designing and implementing the "right supply chains for products".

2.3.1 Lean, Agile, and Leagile

I) *Origin and Key Concepts*

Leanness and agility have been significantly developed and considered as supply chain strategies in the last decade or two. After the early decades of the 1900s, when Fordism matured in many US companies, lean thinking emerged in the middle of the century from Japan and soon dominated manufacturing strategies around the world (Krafcik 1988). The founder of the Toyota Production System, Taiichi Ohno (1988) introduced his lean philosophy as minimising inventories and buffers, eliminating wastes and non-value-added activities (muda), and employing team-oriented decision making processes (Wilson 2010). Impressed by the profound impact that this mass production approach had made on their specific activities (Womack et al. 1991), companies started to make breakthroughs both upstream and downstream of their focal company to achieve a flow of value stream throughout the supply chain (Womack and Jones 1994). The result was significant: lean supply chain management helped many businesses with cost reduction and efficiency improvement, and, therefore, led to price-sensitive markets in the early 21st Century (Myerson 2012).

On the other hand, the history of agile manufacturing is not that long. It was first introduced officially when the report of '21st Century Manufacturing Enterprise Strategy' was published in 1991 and the Agile Manufacturing Enterprise Forum (AMEF) was formed at the Iacocca Institute (Nagel and Dove 1991). Agility enables companies to thrive in a continuously changing environment by focusing on interactive producer-customer relationships (Richards 1996). The adoption of an agile philosophy in supply chain design was first studied by Hoyt (1995) and Sabath (1995). By 1999, as Sanchez and Nagi (2001) reported, nearly 18% of total citations on agile manufacturing was on supply chain management. Despite an extensive literature that worked on agile supply chains, the contributing factors in achieving supply chain agility (Sangari et al. 2014) and the impact of this agility on the firms' performance, e.g., cost efficiency and customer satisfaction, still needs addressing (Gligor et al. 2015).

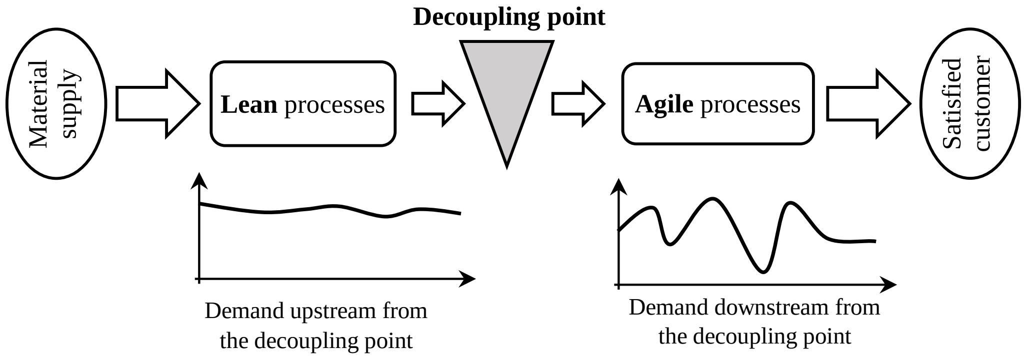

Figure 2.6: Configuration of leagile supply chain [Adapted from Mason-Jones et al. (2000b)]

Each of these two strategies, leanness and agility, has a long and extensive history of theoretical and practical development in a variety of areas, and supply chain management in particular (Lamming et al. 2000). However, we limit our review to the part of the literature that studied how to take advantages of both strategies and/or how to employ them together to design an appropriate supply chain that matches the demand requirements.

Leanness and agility are not always seen as separate. Indeed, the idea of integrating leanness and agility (and calling it a leagile strategy) was first suggested by Naylor et al. (1999) for the purpose of building a "total supply chain". They recommend companies split their supply chain into two parts by strategically positioning the decoupling point, where products are differentiated. Upstream and downstream from this point, the supply chain activities are forecast driven and market driven, respectively. Therefore, the lean paradigm is applicable to the former part (due to less variability in demand), while agility, which focuses on quick response to customer, is suitable for the latter part (because of the high variability and variety in demand and shorter lead times). Figure 2.6 shows a configuration of such a hybrid supply chain. As a result, the further the decoupling point is from the end-user, the more responsive the supply chain will be to the market. Conversely, delaying the decoupling point moves product differentiation closer to the end customer, and leads to more efficiency in the supply chain. As Figure 2.7 displays, the position of decoupling point results in different supply chain strategies.

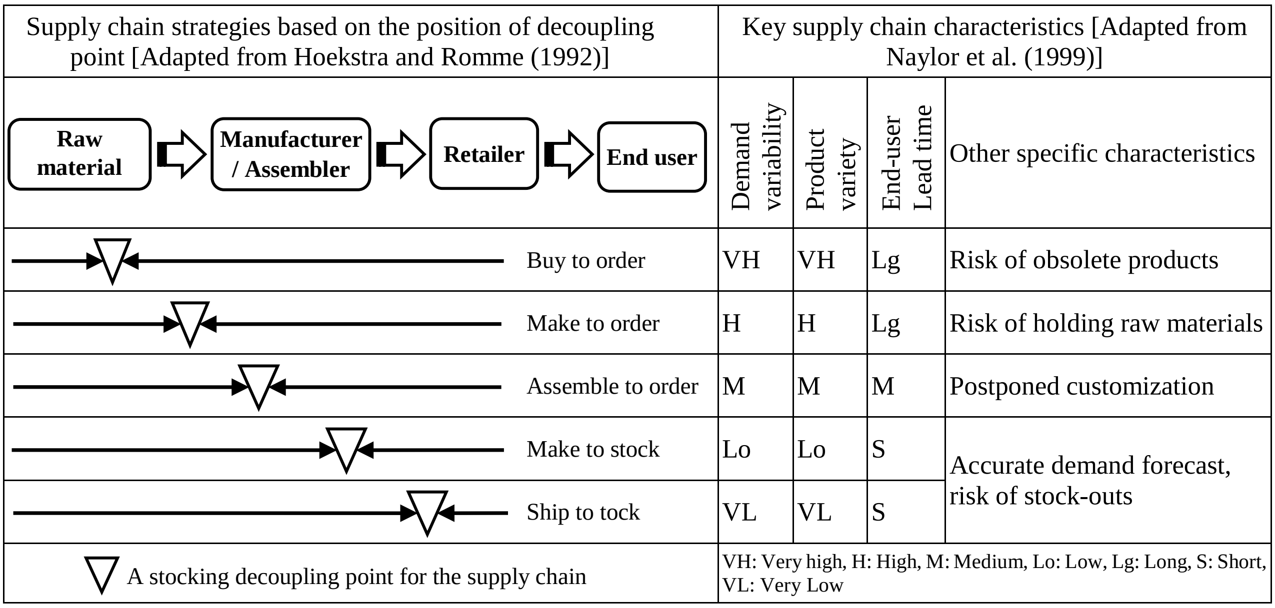

Figure 2.7: Different supply chain strategies and their characteristics according to the position of decoupling point

II) *Supply Chain Implications*

Many studies have been conducted to help organisations employ both leanness and agility to make their supply chain structure match with their demand's characteristics. Mason-Jones et al. (2000a) provided a road map for integrating the two paradigms with an example of re-engineering supply chains in the electronic industry. Adopting the way Hill (1993) introduced various manufacturing strategies based on "order qualifiers" and "order winners", Mason-Jones et al. (2000b) characterised the product type according to the metrics of "market qualifiers" and "market winners". Each metric cost, quality, lead time, and service level may play different roles of qualifier or winner in the market when a company supplies commodities or fashion goods.

There is a good amount of empirical research on how a hybrid strategy of leagility can lead to a better business performance (Fadaki et al. 2019) and how it can be facilitated in the supply chain, e.g., by teamwork, synchronisation, and continuous evaluation (Childerhouse and Towill 2000). Moreover, in a cross-organisational level, some recommended techniques are: appropriately positioning both material and information decoupling points, building a strong connectivity with strategic suppliers (Christopher 2000), taking advantage of postponement, and maintaining integrity (Aitken et al. 2002, Christopher and Towill 2000, 2001).

In order to identify different product types (that require different supply designs), Christopher and Towill (2000) proposed a guide for product classification. The guide clusters products into certain groups using the term DWV^3 which stands for the five key product characteristics: duration of life cycle, time window for delivery, volume, variety, and variability. The classification guide, along with the decoupling point positioning technique and postponement policy (which we discuss more broadly later) were used/adapted in various studies to reconfigure the supply chain. Cases in the lighting industry (Aitken 2000, Childerhouse et al. 2002, Aitken et al. 2003), fast moving consumer goods (Godsell et al. 2011), and apparel industry (Khan et al. 2012) are particular examples.

Recent unsustainability of low-cost off-shore suppliers, and some required degrees of flexibility in the inventory management pipeline, call for a hybrid supply chain strategy where both global and local suppliers operate simultaneously (Christopher et al. 2006). This hybrid configuration will need a formal and dynamic linkage between marketing strategies and supply chain design in a correct “time-space” manner to help businesses follow both agile and lean approaches at the same time (Towill and Christopher 2002). For instance, Huang et al. (2002) compiled this idea of multiple/combined strategy decisions into a three-phase conceptual model (and a simple software program) that offers agile, lean, and hybrid supply chains for functional, innovative, and hybrid products, respectively.

Although the vast majority of literature contributing to this research area uses a conceptual approach with a mostly qualitative methodology, a limited number of works have sought mathematical or modelling approaches. Wang et al. (2004) created a multi-criteria decision making model based on an analytic hierarchy process and preemptive goal programming for selecting supply chain strategies with regard to the product characteristics. Their results confirm that the product types of functional, innovative, and hybrid (which were already defined by Huang et al. (2002) should match the lean, agile, and hybrid supply chain strategies, respectively. The stage of product life cycle that each component is within was used to define the appropriate strategy, e.g., for a functional component which is in the maturity stage, a lean supplier is the best choice.

Agarwal et al. (2006) devised a supply chain performance weighted index to prioritise alternative strategies, i.e., lean, agile, and leagile, for decision makers. They used four core criteria, cost, quality, lead time, and service level, in an analytical network process technique to model the performance of a supply chain strategy. The model shows how changes in the weights of the criteria alter the priority of the strategies, and therefore, helps companies decide on the best supply chain strategy through quantifying their expected performance.

Herer et al. (2002) presented an improved configuration of leagile strategy by replacing postponement of the decoupling point with a tactical approach of "transshipments", which is referred to as the monitored movement of stock between locations at the same echelon level of the supply chain. The modelling of transshipments in leagility demonstrate that this approach can simultaneously decrease cost (by reducing the overall inventory levels) and improve service (by reducing stockout rates and shortening replenishment lead times).

2.3.2 Mass Customization

I) *Origin and Key Concepts*

Looking for the origin of mass customisation, we discovered that Alvin Toffler (1971), in his classic "Future Shock", had anticipated it as a "technological capability" of the future (Pine II 1993b). Later on, Stanley Davis (1987), in his excellent book "Future Perfect", coined the term "mass customisation" describing it as one of the most provocative business models, which offers both wide variety and large quantities of products and services to customers. His inspiration was dealing with the contradiction between having goods and services produced in small volumes, in which case they are customised but have high unit costs, and mass produced, in which case unit costs are brought way down but high volumes make customisation impossible (Davis 1989). He defined mass customisation as a world of paradox which is practically possible when both speed and specificity, as the hallmarks of new technologies, are employed (Davis 1989). Generally, the expected result of mass customization is customised goods and services for customers (even on an individual basis) without a long wait and high price (Kotler 1989).

The concept of mass customisation attained wider popularity when Pine II (1993a) called it “the new frontier in business competition” and provided a guideline for companies to figure out when and how they should shift to mass customisation. He also devised a five-step model through which firms can implement mass customisation based on key value-added activities: development, production, marketing, and delivery (Pine II 1993c). Market turbulence and organisational transformation are two dimensions of the model that begins from service customisation and reaches to modularisation.

The goal of mass customisation is to achieve both low cost and high variety in products or services through stable but flexible processes to quickly respond to individual customer’s needs with near mass production efficiency (Pine II et al. 1993, Pine II 1993a). Coinciding with Pine’s model, another formulation of mass customisation was devised by Kay (1993). The main components of the formulation are a customer-focus and lean production system, a continuous and short-cycle product development, and a flat, empowered management. He also illustrated how two different case companies (dairy and insurance) successfully coped with the same problem: “how to deliver a custom offering to a specific customer at the lowest cost?”

It is recommended that the whole organisation get involved in a successful implementation of mass customisation (Davis 1994, Hart 1995). Thus, researchers have dealt with its potential development from different perspectives. From a marketing view, for example, Gilmore and Pine II (1997) developed a framework of four possible faces of a product that can be portrayed to customers with regard to the degree of change desired in the marketing and product design. Recent advances in information and communication technologies, such as online ordering and social media sharing, have also provided a significant space for further implications of mass customisation. Some good examples of contributions to the development of the concept of mass customisation from different views are Da Silveira et al. (2001), Duray et al. (2000), Fogliatto and Da Silveira (2011), Fogliatto et al. (2012), and MacCarthy et al. (2003).

II) *Supply Chain Implications*

Linking supply chain management and mass customisation will create a synergy for systematically better serving the customer (Tseng and Piller 2003). The structure of a firm's supply chain is highly related to the degree of customisation that it offers to its customers (Salvador et al. 2004). Moreover, simplifying the supply chain is normally required because mass customisation starts with part list standardisation, which minimises the number of parts needed for a new product design (Anderson 2004). Thus, the configuration of a supply chain in order to support the paradigm of mass customisation was widely studied with different approaches (Chandra and Kamrani 2004), which are mostly classified within the following three main groups:

- Concurrent engineering; where product family architecture fulfils customer needs by configuring and modifying well-established modules and components (Tseng and Jiao 1998, Wang et al. 2014, Zhang et al. 2014).
- Time-based manufacturing; where time compression techniques are employed to make lead times as short as possible for quick response to customer (Tu et al. 2001, Zhong et al. 2013).
- Postponement; where standard components are made in the early stages of production, then final products are customised as late as possible when customer order specifications are realised (Brun and Zorzini 2009, Su et al. 2005, van Hoek 2000, 2001).

The impact of supply chain configuration on the firm's capability for mass customisation is one of the issues that many quantitative studies have addressed. Liu and Deitz (2011) found that capability is highly influenced by managerial emphasis on supply chain planning, which leads to both customer-focused product design and reduced supplier lead times. Also, to demonstrate how supply chain scheduling facilitates mass customisation achievements, Yao and Liu (2009) proposed a multi-objective optimization algorithm that optimises punctual delivery and scale production effects for customised demand. Other research shows supply chain planning and cooperation coordination mitigate the impact of organisational flatness on mass customisation capabilities (Yinan et al. 2014). However, Lai et al. (2012)

discovered that supplier integration has an insignificant contribution to the capability for mass customisation.

Yao's (2011, 2013) multi objective optimisation model and ant colony algorithm solved the complexity of a supply chain scheduling problem in a mass customisation practice, and revealed how the benefits of this collaborative method outweighs its potential risks. According to Aigbedo's (2007) mathematical framework and simulation-based case study, when a just-in-time supply chain is desired, typically in the automotive industry, mass customisation increases both the number of part variants and the average inventory of the variants. Therefore, the level of mass customisation is constrained by the cost of excess inventory to avoid stock-outs.

2.3.3 Postponement

I) *Origin and Key Concepts*

The concept of postponement, which is sometimes referred to as delayed product differentiation (Lee 1996), was first introduced by Alderson (1950) and later expanded by Bucklin (1965). The idea is to keep the product unfinished and in a neutral status in the manufacturing process as long as possible until final customer requirements/commitments have been realised. Positioning the decoupling point in the supply chain is a crucial decision for effective postponement (Yang and Burns 2003). Feitzinger and Lee (1997) reported a successful practice of quickly delivering low-price, customised products by postponing the task of product differentiation to the latest possible point of the supply network. As discussed earlier, this supply chain practice also helps with mass customisation where both variety and volume matter in the delivery of products to the customer.

Zinn and Bowersox (1988) identified five general postponement strategies including four operational strategies (labelling, packaging, assembly, and manufacturing) and one time-based (marketing) strategy. Demand uncertainty, product value, number of brands, and number of package sizes were taken into account for choosing the best strategy. Similarly, but with more emphasis on a global view, Cooper (1993) created a model to introduce four supply chain postponement strategies, i.e., bundled manufacturing,

		Logistics	
		Speculation (Decentralized inventories)	**Postponement** (Centralized inventories and direct distribution)
Manufacturing	**Speculation** (Make to stock)	**Full speculation strategy** • *Low production costs* • *High inventory costs* • *Low distribution costs* • *High customer service*	**Logistics postponement strategy** • *Low production costs* • *Low/mid inventory costs* • *High distribution costs* • *Low/mid customer service*
	Postponement (Make to order)	**Manufacturing postponement strategy** • *Mid/high production costs* • *Mid/high inventory costs* • *Low distribution costs* • *Mid/high customer service*	**Full postponement strategy** • *Mid/high production costs* • *Low inventory costs* • *High distribution costs* • *Low customer service*

Figure 2.8: Four generic postponement/speculation-based supply chain strategies and the corresponding implications [Adapted from Pagh and Cooper (1998)]

unicentric, deferred assembly, and deferred packing. He incorporated product characteristics, i.e., formulation and peripherals, into recommendations for designing global logistics strategies.

Consolidating the existing literature, and the two aforementioned works in particular, Pagh and Cooper (1998) devised a framework to help companies rearrange their manufacturing and logistics processes by employing postponement or speculation (which operates on a MTS basis) to achieve high supply chain performance in both delivery of products and cost efficiency. They identified and characterised four generic supply chain strategies, as Figure 2.8 shows, and set up a range of decision determinants based on product specifications, customer requirements, and a firm's capacity. Developing the concept of profile analysis, which looks like Figure 2.9, they devised a two-step procedure for creating and improving alignment between determinants and the appropriate supply chain strategy.

Generally, a postponement program leads to a set of common processes and operations that repeat similarly for all (even distinct) products that will be differentiated after the last delayed common stage. Various techniques have been employed to maximise efficiency and to prolong the common processes. Lee and Tang (1997) modelled the costs and benefits of three product/process redesign approaches (standardisation, modularity, and process restructuring) in a delayed product differentiation strategy. The model formulated a two-product case with normally distributed demand and covered costs of investment, processing, and in-transit/buffer inventory. Their optimisation analysis indicated that in spite of some investment costs and additional processing costs, the company will benefit much more from gaining lower complexity, more flexibility, and higher service level due to the use of such approaches.

II) *Supply Chain Implications*

Ernst and Kamrad (2000) modelled a framework which characterises four different supply chain structures, namely, rigid, postponed, modularised, and flexible, based on combined levels of modularisation and postponement. Also, a "modularisation characteristics curve" was devised based on certain factors i.e., opportunity for modularisation, degree of components customisation, value-adding inputs, and buyer-supplier interdependence (Hsuan 1999) to combine mass customisation, modularisation, and postponement as three interrelated and complementary strategies in supply chain deign (Hsuan and Skjtt-Larsen 2004).

To help postponement work more effectively, especially in today's volatile markets and fast moving technologies, uncertainties throughout a supply chain need to be reduced. Typically, the three main areas that should be considered for uncertainty reduction include companies' internal processes, suppliers' networks, and customers' demand. Also, the key elements of postponement adoption are the position of the decoupling point, supply chain control and integration, and capacity planning (Yang and Burns 2003).

Looking at postponement from the lens of sustainability, it is a helpful strategy for mitigating supply chain disruptions, because it enables a firm to produce a generic form of different products (based on the aggregated demand) and then customise them later on (when the firm is recovering from the disruption). Tang (2006a) recognises postponement as a robust supply chain strategy that helped Nokia overcome the challenge of Philips' (New Mexico semiconductor plant's) failure to deliver critical phone chips (because of the

Product-supply chain decision determinants			**Strategies**			
			Full speculation	**Manufacturing postponement**	**Logistics postponement**	**Full postponement**
Product	**Lifecycle**	Stage	*Introduction*	*Growth*	*Maturation*	*Decline*
		Volume	*Low/Med.*	*Med./High*	*Med./High*	*Low/Med.*
		Cost / Service	*Service*	⟺		*Cost*
	Characteristics	Type	*Standard*	⟺		*Customized*
		Range	*Narrow*	⟺		*Wide*
	Value	Profile	*Initial stages*	⟺		*Final stages*
		Monetary density	*Low*	*Low*	*High*	*High*
Market and demand		Delivery time	*Short*	⟺		*Long*
		Delivery frequency	*High*	⟺		*Med./Low*
		Demand uncertainty	*Low*	⟺		*High*
Manufacturing and logistics		Economies of scales	*Large*	*Small*	*Large*	*Small*
		Special capabilities	*Yes*	*No*	*Yes*	*No*

Figure 2.9: Profile analysis matrix for selecting supply chain strategy [Adapted from Pagh and Cooper (1998)]

fire) in 2000. While Ericsson, another consumer of the chips, lost 400 million Euros in sales, Nokia deployed a contingency plan by reconfiguring a generic cell phone design and delayed product differentiation until a slightly different chip arrived from other suppliers in the US and Japan; thus, Nokia satisfied demand smoothly and achieved a stronger market position (Hopkins 2005). In addition to disruptions, inventory risks (shortage or excess) can be minimised by pooling demand and postponing variety, which of course needs responsive suppliers, especially for high-value and short life cycle products (Chopra and Sodhi 2004).

There are a number of studies on the real world applications of postponement in supply chain management that analyse how this strategy can help organisations with improvement. Some more recent works include Wong et al. (2011a) in the coffee industry, Ferreira and Alcntara (2015) in an orange juice company, Choi et al. (2012) in automobile manufacturing, Guericke et al. (2012) with a decision making optimisation model and a numerical example in the apparel industry, and Kisperska-Moron and Swierczek (2011) and Roh et al. (2014) in multiple sectors of an international market. In an analytical study, Aviv and Federgruen (2012) explored several models that help assess the costs and benefits associated with implementing a postponement strategy. A comprehensive list of studies with different classifications is available in a review by Ferreira et al. (2015) on the literature from 1950.

The theory of postponement strategy has evolved enormously from being developed as a manufacturing technique to being a supply chain management practice (van Hoek 2001, Swaminathan and Lee 2003) that has a discernible impact on a firm's competitive advantage and organisational performance (Li et al. 2006). However, it still needs further consideration from practitioners and researchers on how to address some challenges, such as selecting an appropriate postponement point, assessing postponement application, implementing postponement in the service context, and reducing uncertainty (Boone et al. 2007). A particular claim in this regard is Anand and Girotra's (2007) analytical model that revealed "the strategic weakness of delayed differentiation arises from the inability to make market-specific quantity commitments", and therefore, it may be a dangerous supply chain strategy for managing the effects of demand uncertainty under competition.

2.4 Summary

In this section, we summarise the highlights of the literature that was reviewed in the previous sections. We present them in two separate parts, the key points (i.e., extensions and concerns) regarding Fisher's framework and the relevant insights from other existing supply chain strategies.

2.4.1 Extensions and concerns regarding Fisher's Framework

As one of the most famous guidelines on designing supply chain strategy, Fisher's framework was extensively discussed by the literature. The discussion consists of different approaches, such as examination, validation, extension, and implementation. Therefore, the outcome of such discussion is expected to have a mix of insights about capabilities, weaknesses, or potential developments of the framework, as was discussed in the previous sections. A list of studies that specifically focused on the framework is summarized in Table 2.8.

Our findings from the literature of the framework show that, overall, researchers accept and support Fisher's main idea, i.e., the importance of matching supply chain strategy with product type. However, the way he classifies supply chain strategies and product types, as well as the extent to which this classification is capable of offering the best strategy for every business remains questionable. We found five main concerns/issues that the existing literature has raised in regard to Fisher's framework. These have led to a number of extensions being proposed to improve the framework. In the following paragraphs, we briefly discuss the issues which come in the order of their importance (i.e., how frequent the literature has pointed to them):

I) *Insufficient supply chain strategies.*

It is believed that the framework offers a limited range of alternative strategies for designing a supply chain. Lee (2002) argued that Fisher's (1997) taxonomy is applicable as long as we have a network of mature and well-established processes that form a "stable" supply chain, but more effective strategies are needed when the structure and mechanisms used in a supply chain are still "evolving". These are risk-hedging and agile strategies for functional and innovative products, respectively. An empirical study tested and supported Lee's (2002) framework based on a survey of 243 leading Taiwanese manufacturers who showed a significant improvement on their performance when they aligned their supply chain strategy with product uncertainties (Sun et al. 2009).

There are also a number of studies that suggest an additional supply chain strategy which delivers a group of products that has characteristics of both innovative and functional products. Wong et al. (2006) named this group "intermediate" products. The need for an additional strategy was first discovered by Li and O'Brien (2001) who named it a "physically responsive" supply chain, and modeled it by a manufacture-to-stock (MTS) structure. Harris et al. (2010) also suggested a "hybrid solution" which calls for a type of supply chain that is capable of filling the gap between physically efficient and market responsive supply chains.

Table 2.8: Summary of literature pertinent to the framework

Author(s), year	**Product characteristics**	**Supply chain characteristics**	**New strategies**	**Methodology**
Lamming et al., 2000	- Uniqueness - Complexity	- Speed - Flexibility - Innovation - Quality - Cost - Service		Qualitative
Li and O'Brien, 2001	- Demand uncertainty - Value-adding capacity	- Total cost - Expected lead time - Expected delivery delay	- Physically responsive	Modeling
Randall and Ulrich, 2001	- Product variety	- Distance of production facilities from a target market - Degree of efficient scale in production facilities		Quantitative – US Bicycle industry
Lee, 2002	- Demand uncertainty	- Supply chain uncertainty	- Risk-hedging supply chain - Agile supply chain	Qualitative
Randall et al., 2003	- Market growth rate - Contribution margin - Product variety - Demand and technological uncertainty	- Location of production with respect to the target market - Level of efficiency in the production lines		Quantitative – Bicycle industry
Payne and Peters, 2004	- Volume - Volatility - Order line value - Frequency of order lines - Order line weight - Substitutability of a product - Number of customers buying each product	- Total cost - Inventory investment - Lead time		Quantitative – A telecommunication and electronics company
Blackburn et al., 2004	- Marginal value of time	- Centralization and postponement - Decentralization and preponement	- Efficient reverse supply chain - Responsive reverse supply chain	Qualitative
Wong et al., 2006	- Forecast uncertainty - Demand variability - Contribution margin - Delivery time	- Service level - Buffer level	- Physically responsive - Make to order	Qualitative – A toy manufacturer
Selldin and Olhager, 2007	- Product life cycle - Lead time required - Product variety - Average margin of forecast error - Average stock-out rate - Contribution margin	- Cost - Inventory - Average utilization rate - Lead time - Buffer capacity - Buffer stock		Quantitative – Swedish manufacturers
Qi et al., 2009	- Demand variability - New product's time-to-market - Finished product volume - Introduction interval of new products	- Level of product standardization/personalization - Level of focus on waste and cost reduction - Supplier selection metrics - Frequency of changes in supply chain structure - Level of buffer capacity - Demand volatility - Response pace to the market	- Traditional (neither lean nor agile)	Quantitative – Chinese manufacturers

Sun et al., 2009	- Demand uncertainty - Supply uncertainty	- Price - Flexibility - Quality - Delivery - Service	- Risk-hedging supply chain - Agile supply chain	Quantitative – Taiwanese companies
Stavrulaki and Davis 2010	- Demand uncertainty - Order lead time - Product variety - Volume - Forecast accuracy	- Supply sourcing difficulty - Production costs - Barriers for collaboration and information sharing - Profit margins - Intermediaries between manufacturer and end customer.	- Build to stock - Assemble to order - Make to order - Design to order	Qualitative
Harris et al., 2010	- Forecast margin error - Contribution margin - Stock-out rate	- Gross profit per unit of product	- Hybrid strategy	Quantitative – US Bicycle industry
Lo and power, 2010	- Product life cycle - Lead time required - Product variety - Average margin of forecast error - Average stock-out rate - Average markdown rate - Contribution margin	- Cost - Inventory - Average utilization rate - Lead time - Buffer capacity - Buffer stock		Quantitative – Australian manufacturers
Youn et al., 2012	- Investment on product innovation	- Investment on process improvement	- Eco-efficient - Eco-responsive	Quantitative – Korean companies
Langenberg et al., 2012	- Cost (holding, stock-out, order & procurement) - Demand (distribution) - Lead time (production & assembly)	- Total lead time - Total costs		Modeling
Wright, 2013	- Life cycle - Lead time - Contribution margin - Number of products in the product line	- Manufacturing utilization rate - Product design focus - Amount of inventory		Quantitative – Romanian companies

Based on the same argument, Zhang et al. (2013) formulated a “bi-objective” optimisation model (of cost and lead time) to cover a potential scenario where manufacturers pursue both efficiency and responsiveness. Moreover, from an empirical point of view, there is sufficient empirical evidence that supports the need for a hybrid strategy (Huang et al. 2002, Olhager 2003, Selldin and Olhager 2007, Harris et al. 2010, Lo and Power 2010, Huang 2013).

II) *Insufficient product characteristics.*

The literature has raised a concern about the limited range of factors used for characterising product types. Although the seven factors that Fisher originally suggested fundamentally well describe the type of product, additional factors are sometimes required for a more effective classification. Some examples of additional factors are uniqueness and complexity (Lamming et al. 2000), value-adding capacity (Li and O'Brien 2001), market growth rate and technological uncertainty (Randall et al. 2003), product substitutability (Payne and Peters 2004), new product's time to market and introduction interval (Qi et al. 2009), investment needed for product innovation (Youn et al. 2012), and number of products in the production line (Wright 2013).

III) *Operationalisation challenge.*

Another potential issue that Fisher's framework has is the lack of sufficient instructions on how to operationalise the appropriately selected supply chain strategy (efficient or responsive). This becomes more important when a firm requires to transit from an existing mismatching state to a matching state and, therefore, needs to know how to conduct this transition phase effectively. This may explain why, as Wright (2013) reported, companies had significant intention to resolve their product-supply chain misalignment, but they don't take action. Furthermore, Stavrulaki and Davis (2010) asserted that Fisher does not explain how production and logistics processes can support efficiency nor explicitly defines how responsiveness should relate to flexible processes. The significant difference that the two types of processes have in both practice and thinking (Ramdas and Spekman 2000) necessitates the need for further instructions.

One may argue that the framework was aimed at providing a strategic insight for managers rather than formulating a pathway to implementation; hence, it leaves an open space for further research, as for example, Gimenez and Ventura (2005), Lambert et al. (2005), Waller et al. (2008), and Stavrulaki and Davis (2010) addressed. Nevertheless, the significant difference that the two types of processes have in both practice and thinking (Ramdas and Spekman 2000) further necessitates the need for the instructions.

IV) *Generalisation challenge.*

A further challenge appears when generalising the framework to a wide variety of industrial sectors, which have inherently different critical factors associated with their products or supply chains. Specifically, for agricultural and food products, there are some particular concerns that differ from general ones for other products, e.g., IT equipment and

PC hardware components. Salin (1998) argued that Fisher's typology is not applicable in agri-food supply chains because of some unique features such as food quality and safety, weather-related supply variability, biological variations in cost and time, perishability, and seasonality. Fresh milk and meat in a typical supermarket usually have very long product life cycle, and also have stable, predictable demand with very low margin, thus are well fitted to the definition of functional products. However, their shelf life is extremely short, calling for a very fast delivery, and their holding/ordering costs are relatively high, raising the total inventory cost throughout the supply chain, which is supposed to be cost efficient.

V) *Non-supporting evidence.*

The last, but perhaps the most critical issue, is that the literature has some reports which do not support Fisher's framework. Lo and Power (2010) provided the strongest evidence against the framework by reporting the lack of any support to the framework from Australian manufacturers. Their conclusion was that, after almost twenty years, the framework is not capable any more of reflecting today's business environment. Further evidence is Wright's (2013) research in Romania that could not prove that companies who have matching supply chains with product type outperform those who do not have.

In summary, although the amount of supporting evidence in the literature outweighs the non-supporting evidence, and some successful applications of the framework have been successfully carried out (Blackburn et al. 2004, Milner and Kouvelis 2005, Youn et al. 2012, Zhang et al. 2013), there is not yet a consensus on its validity. Eriksson (2018) claims that the literature has both supporting and inconclusive results in this regard.

We believe that the framework actually lacks a strong analytical support. Why is analytical support important? Firstly, because the majority of the existing evidence (either supporting or non-supporting) is from empirical analysis that only represents the context of the study, hence, provides various (and sometimes contradicting) claims regarding the capability of the framework. Some examples that we discussed earlier include Wagner et al. (2012) studying US and EU manufacturers and reporting a good support, Wright (2013) studying Romanian manufacturers and witnessing no support, and Lo and Power (2010) studying Australian manufacturers and claiming a rejection (of the framework being used as a valid reference in practice). In a recent review of the literature, Prajogo et al. (2018) report that the existing empirical studies question the validity of the framework in several ways and claim that there is a need for confirmatory evidence.

Secondly, the only two existing mathematical studies that explicitly test the framework still have several gaps, i.e., they either obtain most of their results from numerical sensitivity analysis (Li and O'Brien 2001) or still provide no informative guide on the optimal decisions (Langenberg et al. 2012). Further, neither of them covers the impact of product life cycle as one of the product characteristics that Fisher suggests. The aim of this study (regarding the second research question) is to fill in these gaps and investigate whether we can validate the framework with a proof that is case (study) independent and provides a rigorous, informative prescription for how the optimal supply chain decisions should be defined.

2.4.2 Implications of product-driven strategies

In this chapter we performed a broad review of the literature of product-driven supply chain strategy. Figure 2.10 illustrates the structure of the review that has a particular focus on Fisher's framework. There are several lessons we can take from this review. First, it has been always both a big goal and a major issue in operations management how to design supply chains in alignment with customers' needs and firms' core competences, and, more importantly, to maintain this alignment while market requirements change. Dealing with this issue necessitates a clear consensus throughout the supply chain on the strategic objectives, continuous observation/prediction of the market, and swiftly making appropriate adjustments. This is known as the Triple-A supply chain (Lee 2004), which is particularly constructive when market qualifiers and winners vary in different markets and even alter very quickly in a certain market.

Second, the three supply chain strategies, i.e. postponement, mass customisation, and leagility, appear to convey the same paradigm of supply chain management by combining the two fundamental (and conventionally known as mutually exclusive) strategies, i.e. efficiency/leanness and responsiveness/agility. Generally, they provide a solution that simultaneously satisfies companies' traditional need for cost reduction and customers'

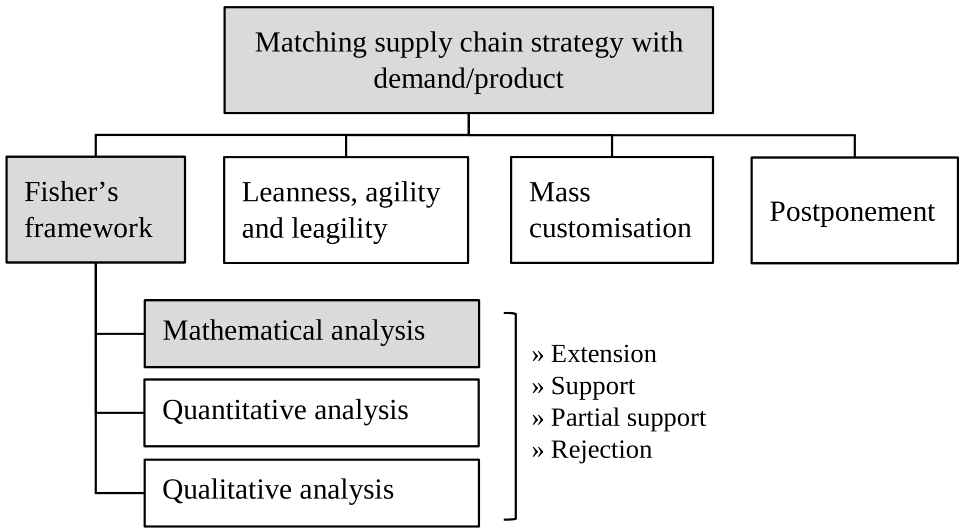

Figure 2.10: The structure of the literature review

increasing need for quality, flexibility, delivery, innovation, etc. This solution, which fundamentally considers product characteristics, has been supported by some empirical evidence that we discussed in this chapter. The evidence agrees that effective supply chain strategies should take into account multiple criteria.

Third, to design an effective product-driven supply chain strategy, there are a number of characteristics of product and supply chain to be taken into account. Not all of them are necessarily applicable for every business (nor limited to the existing number in the literature), but it is important to recognize the maximum number of determinants for each particular product. Table 2.9 lists some of the most frequently quoted characteristics in the literature. Consequently, whatever we call our supply chain strategy it needs to fit the product characteristics.

Table 2.9: Product/supply chain characteristics

Product characteristics	Supply chain characteristics	Supply chain strategies	Reference
- Life cycle - Type (Customized or Standard) - Range (of variety) - Value profile - Monetary density - Delivery time & frequency - Demand uncertainty	- Level of economies of scale - Having special capabilities	- Full speculation (MTS) - Manufacturing postponement - Logistics postponement - Full postponement	Pagh and Cooper (1998)
- Demand variability - Product variety - End-user lead time - Product quality	- Lead time - Service - Cost - flexibility	- Lean - Agile - Leagile	Naylor et al. (1999)
- Duration of life cycle - Time window of delivery - Volume - Variety - Variability	- Service level - Cost	- Lean - Agile - Leagile	Christopher and Towill (2000a)

Chapter 3

Strategy Development and Optimization

In the previous chapter, we reviewed a number of different supply chain strategies that are driven by the characteristics of demand and product type. With a particular focus on Fisher's (1997) framework, as one of the most well-known guidelines, we demonstrated that the existing literature is both diverse, ranging from full support to no support, and wide, suggesting many extensions from different angles. Although the evidence of empirical support for the framework outweighs the non-supporting reports, the framework still lacks a strong analytical validation. We aim to close this gap by exploring its analytical validity.

In this chapter, we develop a two-echelon supply chain model to conduct our analysis and explore the extent to which it supports the framework. While formulating the model, we expand on continuous review systems by implementing a lead-time-based optimisation approach and incorporating the effect of the trade-off between stockout and obsolescence costs on inventory decisions. Therefore, we start the chapter by looking at the background of the model and how it will contribute to the existing literature. The model is then optimised with respect to two decisions, order quantity and lead time.

3.1 Theoretical Background

In this section, we report on the existing studies that our model technically relates to. Apart from the product type and supply chain alignment literature that we broadly reviewed in the previous chapter, we recognise two more streams of relevant research. These are i) Lead-time-based supply chain decisions, and ii) Stockout and obsolescence costs trade-offs.

I) *Lead-time-based supply chain decisions.*

The role of lead time in operations decisions was initially studied in inventory management by evaluating the impact of (procurement) lead time variations on the optimal choice of inventory policies (Hadley and Whitin 1962, Kaplan 1970, Liberatore 1977, Foote et al. 1988) and the total inventory cost (Vinson 1972, Das 1975). Then a lot of research was conducted on employing different probability distributions of demand and/or lead time under different planning settings, e.g., continuous/periodic review, lost sale or backlog, timely constant/variable cost component(s). As a broad review, readers are referred to Sarkar and Moon (2014) for a list of decision/parameter settings, Hayya et al. (2011) for a list of objective functions, and Glock (2012) for a comparative discussion on methodologies and modeling approaches.

Among the existing research, our work is closer to a stream that Liao and Shyu (1991) began by developing a model to minimise total cost of a continuous review system with respect to lead time, when order quantity is a predetermined parameter. Ben-Daya and Raouf (1994) extend the model by considering both lead time and order quantity as decisions when shortages are neglected. Further extensions are given in Ouyang et al. (1996) and Hariga and Ben-Daya (1999) by incorporating stockout costs (under lost sales and backorder), and in Ouyang and Wu (1997, 1998) and Lan et al. (1999), by adding service level constraints and evaluating the effect of safety stock on the inventory decisions.

Later, the concept of jointly (i.e., time and quantity) optimal inventory modeling was expanded in many different ways. For instance, Pan and Yang (2002, 2004) introduce a new decision, the number of shipments, and then Ouyang et al. (2007) add another, reorder point, to study the impact of quality-related costs as well as quality improving investment when implementing a just-in-time paradigm. In terms of the influencing factors, Chandra and Grabis (2008) consider time-dependent procurement costs, Huang et al. (2010) report on the impact of order-processing cost reduction with possible delayed payments, and Hayya et al. (2011) study the impact of lead time reduction (in both average and variability) under order crossover, which is further discussed later (e.g., Disney et al., 2016). The concept gradually comes to the context of supply chain and develops in various areas, such as vendor-managed inventory (Rad et al. 2014), value of information sharing (Sabitha et al. 2016), integrated multi-stage networks (Zhao et al. 2016), and supply chain responsiveness optimisation (Hum et al. 2018).

Lead time is also a key element of dual sourcing problem, where the objective is to minimise the expected sum of procurement, holding, and shortage costs by making a choice between a fast but expensive (usually called expediting or express) supplier and a slow but cheap (usually called regular) supplier, or a combination of both (Boute and Van Mieghem 2014). Emerging from Fukuda's (1964) dual-base-stock policies, which set up regular and expedite base-stock levels for managing inventory position, this problem has been addressed in many different angles, such as, continuous review system for two suppliers (Moinzadeh and Nahmias 1988, Moinzadeh and Schmidt 1991), multiple suppliers under stochastic demand and lead time (Song and Zipkin 2009), employment of an expediting (and expensive) mechanism to fill shortages when they happen in a periodic-review system (Huggins and Olsen 2003) or in the downstream facilities of a supply chain (Huggins and Olsen 2010).

What makes our work different from the research stream reviewed above is twofold: first, incorporating obsolescence cost, which occurs when a product reaches the end of its life cycle, while finding the optimal ordering/sourcing strategy on a continuous basis; and, second, analyzing the impact of product characteristics on the decisions in the optimal strategy. The characteristics include demand variability, product life cycle, and contribution margin, which are among Fisher's (1997) proposed list of characteristics. Interestingly, in their recent study, von Falkenhausen et al. (2019) show that both demand variability and contribution margin (together with delivery lead time) are the most important factors for supply chain strategy development and product life cycle, although less important, has a significant effect on service level.

II) *Stockout and obsolescence costs trade-offs.*

The magnitude and prevalence of stockouts are considerable in retailing. According to Gruen et al. (2002), the average out-of-stock rate in the United States and Europe is around 8% and the associated losses can be substantial, e.g., an average of 4.5% lost sales in hair care. Also, Corsten and Gruen (2003) reported that, when facing a stockout, only 15% of customers would delay their purchase, the rest would either make a substitution (of another store, another item–same brand, or another item–different brand) or decide not to purchase.

Fitzsimons (2000) claims that experiencing a stockout substantially discourages customers to return for their next shopping, and Olsen and Parker (2008) confirm the detrimental effect of the consumers leaving the market on the future demand. Interestingly, Huang and Zhang (2016) show that stockouts can even affect the customers who don't have any strong desire or prior plan to buy (e.g., are just browsing the offerings and coincidently notice) the out-of-stock item.

Clearly, inventory plays a key role in dealing with stockouts, but the downside of holding safety inventory is, on top of the associated carrying costs, the imposed extra cost of unsold stock. From a marketing perspective, planned obsolescence, where products are designed to have rapidly diminishing consumer value inducing customers to repeat their purchases, is one effective strategy (Agrawal et al. 2016). In contrast, firms can think of designing highly-durable products as another strategy, in which a company privately chooses to do less frequent introduction of new editions/products and bears lower risk (and volume) of obsolete inventories (Waldman 2003).

From an operations point of view, managers should balance keeping the service level high (by maintaining sufficient available inventory) with avoiding the risk of obsolete inventory (by minimising stock level) for the product being phased out (Pourakbar et al. 2014). Although this balance has not been widely addressed, there are several works that study obsolescence under certain operational settings, such as fluctuating demand rate (Song and Zipkin 1993, 1996), planned backlogged stockouts (van Delft and Vial 1996), random life time perishability (Jain and Silver 1994, Dohi and Osaki 1995, Persona et al. 2005), sudden total loss of unsold items under periodic- and continuous-review controls (Song and Lau 2004), supply chain postponement strategy (Wong et al. 2011b), and multiple sourcing strategies for parts (Shen and Willems 2014).

In our model, the average obsolescence cost is defined under a continuous review system while maintaining analytical tractability that also allows for ease of use in practice. More specifically, we contribute to this part of the literature by redefining the traditional EOQ in a new formulation, which incorporates obsolescence cost, and derive the optimal lead time that minimises total inventory cost.

3.2 The Model

In this section, we introduce an inventory cost model for a supply chain that consists of two tiers and a single product. The cost model comprises four main components, namely, the cost of carrying inventory in house and in the pipeline; the cost of ordering and shipping inventory in each replenishment; the cost of obsolete inventory at the end of the product life cycle; and the cost of stockouts when (a proportion of) demand cannot be satisfied immediately from the shelf. The two tiers are a supplier (she) and a retailer (he), collaborating on cost minimisation, with full information sharing when making decisions. The product is defined by three characteristics: demand variability, contribution margin, and life cycle. We keep the formulation of our model simple and tractable to be able to provide in-depth analysis and insights that can be extended to other settings.

In our model, the supplier operates on a make-to-order basis, which means she commences processing an order only once it is placed by the retailer. The lead time to fulfil an order is neither constant nor deterministic. In this section, we assume that lead time is stochastic with mean μ_L and standard deviation σ_L (years), and later, in the next section, we consider it as a non-random decision variable. The demand is also random with annual mean μ_D and standard deviation σ_D, and is directly satisfied by the retailer. If the product is temporarily out of stock, we assume a complete lost sale, which implies that the customer decides to buy the item elsewhere. Our model, however, has the potential to be easily developed to capture the case of backordering, where the customer will wait for product.

The retailer adopts a continuous review system, i.e., he constantly monitors his inventory position and places orders of size Q to the supplier any time the position drops to the reorder point R. In the remainder of this paper, we broadly discuss Q, which is a major decision in our model. The reorder point, however, will simply follow the standard decision rule that suggests $R = LTD + SS$, where LTD is the lead time demand (or average demand over lead time) and SS is the safety stock. This (R, Q) system is a good choice for this study because, first, from a practical view, when defining R, the retailer would be able to make an accurate count of inventory to better deal with LTD uncertainties, especially when both demand and lead time have variations. Second, for the purpose of modeling, Q is the best common variable to formulate the multiple cost components, and also, is well defined in conjunction with the lead time, which will later (in Section 4) become a second decision variable.

The ordering cost is composed of a fixed amount of s per replenishment and a variable amount of r per unit of product. The former is a set-up cost and independent of the order size, while the latter is a shipping cost that applies to each unit supplied. The selling price, production/procurement cost, and salvage value (of the obsolete inventory at the end of product life cycle) per unit are p, c, and v, respectively. Holding one unit of product per unit of time (year) incurs a cost of h, which is proportional to the unit cost, i.e., ic, where i is the inventory carrying cost rate per year.

Let l_c denote product life cycle, the number of years that the product is expected to last in the market. This parameter is constant and fixed by management to allow for planned obsolescence to effectively happen at the scheduled time of the substitution of a new product. For the sake of model simplicity, let us assume that all defined parameters including costs, unit price, and other estimates (of demand and lead time) stay unchanged over the product life cycle; therefore, there is no need to formulate any time dynamics in the parameters. Further, this assumption is not too unrealistic because it can easily be part of the agreement that both parties (i.e., retailer and supplier) usually make at the beginning of their collaboration.

Building on the above-described supplier-retailer structure, we formulate our model, starting by holding cost. This cost is associated with average inventory, $Q/2 + k\sigma_x$, where σ_x is the standard deviation of LTD and is determined by $\sqrt{\mu_L \sigma_D^2 + \mu_D^2 \sigma_L^2}$, k is a safety factor, and the term $k\sigma_x$ represents SS that accommodates variations of demand during lead time (Chopra and Meindl 2016). Thus, the expected holding cost over a year is

$$\left(\frac{Q}{2} + k\sigma_x\right) h.$$

The ordering cost occurs every time a replenishment order is placed and equals $(rQ+s)$, which leads to an annual average cost of

$$(rQ + s)\frac{\mu_D}{Q}.$$

The obsolescence cost is computed based on the average obsolete inventory at the end of product life cycle. Since we assumed a planned obsolescence in this model, this inventory would be the average of zero (all stock being sold out – the best case) and Q (final order left unsold – the worst case). Therefore, on an annual basis, we would expect an obsolescence cost of

$$\frac{Q}{2l_c}(p - v).$$

Finally, to account for the cost of stockouts, we apply the definition of expected shortage cost per replenishment proposed by Silver et al. (1998a). They believe that the cost consists of the expected shortage per replenishment cycle and the cost per unit short. The former is measured by $\sigma_x G_u(k)$, when forecast errors are assumed normally distributed, and the latter is $p - c$, assuming that customers buy the out-of-stock items elsewhere. Also, the function $G_u(k)$, which is used in finding the expected shortages per replenishment cycle for a certain value of k, is determined by

$$G_u(k) = \int_k^\infty U f(u)du - k\int_k^\infty f(u)du,$$

where $f(u)$ is the standard normal density function.

Further, according to Fisher (1997), contribution/profit margin, m, which is usually called the variable contribution margin ratio in accounting texts, is defined as price minus unit cost divided by price, $m = \frac{p-c}{p}$, thus, the cost per unit short, $p - c$, equals mp and the expected shortage cost per replenishment becomes $mp\sigma_x G_u(k)$.

The annual expected cost of stockouts is, therefore,

$$mp\sigma_x G_u(k)\frac{\mu_D}{Q}.$$

It may seem reasonable to use this expression only under complete lost sales since any unit short is subject to the whole profit lost. However, under the backlog policy too, if we opt to lose the profit (by offering the product at its original unit cost, c) as the compensation for our delayed delivery, the result would be the same as the above. Alternatively, if losing the whole profit seems unrealistic and too much for a backlog, we can assume that the cost (of unit short) is proportional to the profit by inserting a fractional term in the formula above.

Having defined all the major cost components separately, we now formulate the expected total cost model,

$$E[TC] = \left(\frac{Q}{2} + k\sigma_x\right) h + (rQ + s)\frac{\mu_D}{Q} + \frac{Q}{2l_c}(p - v) + \frac{mp\sigma_x G_u(k)\mu_D}{Q}, \tag{3.1}$$

where the key decision is order quantity, Q, made by the retailer and assumed to be the same in all replenishment cycles. This decision should balance the cost of holding inventory as well as facing obsolescence at the end of the life cycle, from one side, with the cost of ordering/shipping inventory as well as running out of stock, from the other side. Therefore, defining the optimum order size is crucially important when managing inventory. Obviously, it is not the only decision for supply chain management, and a number of other decisions need to be made in practice. One of them is lead time, which determines how quickly the markets and customers should be served and therefore how fast the supplier(s) should respond to a retailer's order. This decision is also critical, particularly, when the level of responsiveness of a supply chain is the main concern. We will broadly discuss these two decisions, order size and lead time, in the following sections.

3.3 Optimal Decisions

In this section, we utilize the model presented in the previous section to investigate how to best make decisions on the order quantity and lead time such that the supply chain expected total cost is minimised. We do this in three major steps: 1) Finding the optimal order quantity, 2) Finding the optimal lead time for a given order size, and 3) Finding jointly optimal order quantity and lead time. Further, we analytically explore the impact of certain product/demand characteristics on the optimal decisions in each of the above three steps. This exploration will allow us to draw a conclusion on whether and the extent to which our findings support Fisher's framework.

3.3.1 Optimal Order Quantity

The objective of this step is to find the best order size, Q, that the retailer should place to the supplier. Recalling the supply chain model described in the previous section, we aim to minimise the expected total cost based on Q as the main decision.

PROPOSITION 3.1 *The expected total cost function* $E[TC]$ *has a global minimum,* Q^**, that satisfies*

$$Q^* = \sqrt{\frac{2\mu_D(mp\sigma_x G_u(k) + s)}{h + \frac{p-v}{l_c}}}. \tag{3.2}$$

PROOF OF PROPOSITION 3.1

Rewriting (3.1) with respect to Q, we have

$$E[TC_Q] = \frac{1}{2}\left(h + \frac{p-v}{l_c}\right)Q + (mp\sigma_x G_u(k) + s)\mu_D \frac{1}{Q}.$$

Solving the first derivative of $E[TC_Q]$ returns a critical point, Q^* (defined by (3.2)), which is certainly a global optimum because the second derivative,

$$(mp\sigma_x G_u(k) + s)\mu_D \frac{2}{Q^3},$$

is strictly positive for all $Q > 0$, including Q^* that is, therefore, a global minimum for $E[TC]$. □

Substituting Q^* for Q in (3.1) returns the optimal total cost

$$E[TC_{Q^*}] = \sqrt{2\mu_D(mp\sigma_x G_u(k) + s)\left(h + \frac{p-v}{l_c}\right)} + hk\sigma_x + r\mu_D.$$

If we consider any uncertainty-related cost (as well as the variable shipping cost, r) as zero, then (3.2) would become $\sqrt{\frac{2\mu_D s}{h}}$, which is the standard EOQ formula. Also, the optimal total cost would change to $\sqrt{2\mu_D sh}$, which is the optimal cost of the EOQ model, where demand and lead time are both deterministic and shortage is not allowed, thus, neither safety and obsolete inventory nor stockout exists (Nahmias and Olsen 2015).

As far as the impact of product/demand characteristics is concerned, the optimal total cost is expected to decrease in product life cycle, but increase in demand variability and profit margin. Therefore, shifting from a functional product (with long l_c, small m, and low σ_D) to an innovative product (with short l_c, large m, and high σ_D) will increase the supply chain expected total cost. Further exploration of the impact on the optimal order quantity (Q^*) reveals that, if the order quantity is the only decision to make, the shift would require larger orders because the cost of running out of stock increases for innovative products. Thus, focusing on efficiency, which calls for lean processes to reduce inventory level and relevant costs, would not be the correct strategy when developing supply chains for innovative products.

3.3.2 Optimal Lead Time

In this step, we explore the cost minimisation objective with respect to lead time. As discussed earlier in the literature review, when demand is uncertain, setting a short lead time improves service level, but requires investment in fast/expediting facilities that are expensive and incur extra shipping costs. On the other hand, operating on a long lead time is cheaper, but causes a lot of unserved/under-served demand and imposes stockout costs. Hence, finding the optimal lead time is very important to acquire an appropriate level of supply chain responsiveness at reasonable cost. Suppose that, in our supply chain model, lead time is now a decision variable, L, and order size is a given parameter, q. The goal is to find the optimal lead time and explore how it is influenced by demand/product characteristics. The starting point towards this goal is reformulating the model with respect to the lead time. To do so, we make two updates on the existing parameters in (3.1). First, to reflect the impact of lead time decisions on the replenishment costs, we assume that the variable ordering cost, r, is a function of lead time and is defined by the simple form of $r = \frac{w}{L}$, where w is a unit shipping cost parameter. Since the supplier can replenish orders at different paces (e.g., regular, fast, and express), the function accommodates the different corresponding time-dependant costs, dictating that r increases when delivery is faster.

Second, as the lead time is no longer a probabilistic parameter (so, we assume $\sigma_L = 0$), then, $\sigma_x = \sigma_D\sqrt{L}$, which means variations of lead time demand only depend on demand variability. Taking these two updates into account and reformulating the total cost model, presented in (3.1), with respect to L, we have

$$E[TC_L] = w\mu_D\frac{1}{L} + \left(\frac{mpG_u(k)\mu_D}{q} + hk\right)\sigma_D\sqrt{L}. \tag{3.3}$$

Since the cost function is now with respect to L, we remove (from (3.1)) the terms that are not dependent on L. The proposition below (and its proof) expresses (and explores) the optimality of this function.

PROPOSITION 3.2 *The expected total cost function $E[TC_L]$ has a unique global minimum, L^*, that satisfies*

$$L^* = \left[\frac{2w\mu_D}{\left(\frac{mpG_u(k)\mu_D}{q} + hk\right)\sigma_D}\right]^{\frac{2}{3}}. \tag{3.4}$$

PROOF OF PROPOSITION 3.2

The first and the second derivative of $E[TC_L]$ with respect to L are presented below. For simplicity, we rename $E[TC_L]$ as ψ.

$$\psi' = \frac{d\psi}{dL} = -w\mu_D\frac{1}{L^2} + \left(\frac{mpG_u(k)\mu_D}{q} + hk\right)\sigma_D\frac{1}{2\sqrt{L}}$$

$$\psi'' = \frac{d^2\psi}{dL^2} = 2w\mu_D\frac{1}{L^3} - \left(\frac{mpG_u(k)\mu_D}{q} + hk\right)\sigma_D\frac{1}{4\sqrt{L^3}}$$

The only critical point that is obtained from $\psi' = 0$ is L^* (determined by (3.4)), which, therefore, is a global minimum for ψ, because

$$\psi''(L^*) = \frac{3}{8w\mu_D}\left(\frac{mpG_u(k)\mu_D}{q} + hk\right)^2\sigma_D^2 > 0.$$

$\square$

According to the expression for optimal lead time in (3.4), both demand variability and contribution margin negatively influence the optimal lead time. In other words, the optimal lead time will be shorter when demand has higher variability and/or product has greater contribution margin. This is, in fact, analytical support for Fisher's framework, which suggests innovative products (with high demand uncertainty and large contribution margin) need responsive supply chains that are capable of offering short lead times.

3.3.3 Jointly Optimal Order Quantity and Lead Time

In this step, we study whether and how order size and lead time can jointly minimise the supply chain expected total cost. This means optimising the bi-variable objective function,

$$E[TC_{Q,L}] = \frac{w\mu_D}{L} + \frac{s\mu_D}{Q} + \left(h + \frac{p-v}{l_c}\right)\frac{Q}{2} + hk\sigma_D\sqrt{L} + mpG_u(k)\mu_D\sigma_D\frac{\sqrt{L}}{Q}, \quad (3.5)$$

which is a reformulation of (3.1), by assuming that Q and L are both decision variables. The following proposition states the joint optimality of the the two variables.

PROPOSITION 3.3 *If the two conditions,*

$$s > \frac{h + \frac{p-v}{l_c}}{\mu_D}$$

and

$$\left(\frac{2\mu_D s}{h + \frac{p-v}{l_c}}\right)^{\frac{1}{2}} > \frac{4.5hk}{mpG_u(k)\mu_D},$$

hold, the expected total cost function $E[TC_{Q,L}]$ *has a global minimum that solves the following system of equations:*

$$\begin{cases} Q^* = \left[\dfrac{2\mu_D(mpG_u(k)\sigma_D\sqrt{L^*} + s)}{h + \frac{p-v}{l_c}}\right]^{\frac{1}{2}}; \\ L^* = \left[\dfrac{2w\mu_D}{\left(\frac{mpG_u(k)\mu_D}{Q^*} + hk\right)\sigma_D}\right]^{\frac{2}{3}}. \end{cases} \quad (3.6)$$

Proof of Proposition 3.3

Let us first explore the joint convexity of $E[TC_{Q,L}]$ in the two variables. Equation (3.5) consists of five terms. The summation of terms 2 and 3,

$$\frac{s\mu_D}{Q} + \left(h + \frac{p-v}{l_c}\right)\frac{Q}{2},$$

is clearly convex in Q. If we can show that the summation of terms 1, 4, and 5,

$$g(Q,L) = \frac{w\mu_D}{L} + hk\sigma_D\sqrt{L} + mpG_u(k)\mu_D\sigma_D\frac{\sqrt{L}}{Q},$$

is jointly convex in Q and L, then the joint convexity of (3.5) is proven. To do so, we need to show that $\partial^2 g/\partial L^2 > 0$ and $|H^g| > 0$, where, H^g is the Hessian matrix (made of the partial derivatives) for $g(Q,L)$. The former requires

$$2w\mu_D\frac{1}{L^3} - \left(\frac{mpG_u(k)\mu_D}{Q} + hk\right)\sigma_D\frac{1}{4\sqrt{L^3}} > 0,$$

which returns a boundary for L,

$$L_0(Q) = \left[\frac{8w\mu_D}{\left(\frac{mpG_u(k)\mu_D}{Q} + hk\right)\sigma_D}\right]^{\frac{2}{3}},$$

such that $L < L_0(Q)$ implies $\partial^2 g/\partial L^2 > 0$. The latter (Hessian requirement) is equivalent to

$$\left[\frac{2w\mu_D}{L^3} - \frac{hk\sigma_D}{4L^{\frac{3}{2}}} - \frac{mpG_u(k)\mu_D\sigma_D}{4QL^{\frac{3}{2}}}\right] \times \left[\frac{2mpG_u(k)\mu_D\sigma_D\sqrt{L}}{Q^3}\right] - \left[\frac{mpG_u(k)\mu_D\sigma_D}{2\sqrt{L}Q^2}\right]^2 > 0,$$

which dictates a boundary for Q,

$$Q_0(L) = \frac{3}{mpG_u(k)\mu_D\sigma_D}\left(\frac{w\mu_D}{L^{\frac{3}{2}}} - \frac{hk\sigma_D}{8}\right),$$

such that $Q > Q_0(L)$ implies $|H^g| > 0$. As a result, for any $(Q,L) \in \{L < L_0(Q), Q > Q_0(L)\}$, we have $|H^g|$ positive definite, thus, $g(Q,L)$ is strictly convex, and consequently, so is $E[TC_{Q,L}]$. Since we have previously defined Q^* and L^* by (3.2) and (3.4), respectively, if $E[TC_{Q,L}]$ has a minimum, i.e., (Q^*, L^*), then it is explicitly defined by solving the two-equation-two-unknown system in (3.6). If the solution exists and falls in the convexity region, it will be a unique global minimum for $E[TC_{Q,L}]$.

The existence of the solution for the system requires $Q^* = Q^*(L^*)$, or equivalently,

$$Q^* - \left[\frac{2\mu_D \left(mpG_u(k)\sigma_D \left[\frac{2w\mu_D}{\left(\frac{mpG_u(k)\mu_D}{Q^*} + hk \right) \sigma_D} \right]^{\frac{1}{3}} + s \right)}{h + \frac{p-v}{l_c}} \right]^{\frac{1}{2}} = 0,$$

to be solvable. We know that for two extreme cases of $Q^* = \infty$ or $Q^* = 0$, the left hand side of the equation above becomes positive and negative, respectively, thereby, crosses the line $Q = 0$. Thus, $Q^* = Q^*(L^*)$ is certainly solvable.

Finally, the solution falls in the convexity region, if we prove $(Q^*, L^*) \in \{L < L_0(Q), Q > Q_0(L)\}$. A comparison between $L_0(Q)$ and $L^*(Q)$ indicates that

$$L_0(Q) = 4^{\frac{2}{3}} L^*(Q),$$

which confirms $L^*(Q) < L_0(Q)$ for any Q, including Q^*. Thus, the solution meets the bounding limit on L. The limit on Q is also met if $Q^*(L^*) > Q_0(L^*)$. It is clear that

$$Q^*(L^*) > \left(\frac{2\mu_D s}{h + \frac{p-v}{l_c}} \right)^{\frac{1}{2}}.$$

Also, from plugging L^* into $Q_0(L)$, we have

$$Q_0(L^*) = \frac{3}{2Q^*} + \frac{9hk}{8mpG_u(k)\mu_D}.$$

Thus, $Q^*(L^*) > Q_0(L^*)$ is proven, if

$$\left(\frac{2\mu_D s}{h + \frac{p-v}{l_c}} \right)^{\frac{1}{2}} > \frac{3}{2Q^*} + \frac{9hk}{8mpG_u(k)\mu_D}$$

which is equivalent to

$$Q^* > \frac{12}{8\left(\frac{2\mu_D s}{h+\frac{p-v}{l_c}}\right)^{\frac{1}{2}} - 9\frac{hk}{mpG_u(k)\mu_D}}. \tag{3.7}$$

Now, if (as assumed in the proposition)

$$\left(\frac{2\mu_D s}{h+\frac{p-v}{l_c}}\right)^{\frac{1}{2}} > \frac{9}{2}\frac{hk}{mpG_u(k)\mu_D} \tag{3.8}$$

holds, then

$$Q^* > \frac{2}{\left(\frac{2\mu_D s}{h+\frac{p-v}{l_c}}\right)^{\frac{1}{2}}}, \tag{3.9}$$

implies (3.7), because

$$\frac{2}{\left(\frac{2\mu_D s}{h+\frac{p-v}{l_c}}\right)^{\frac{1}{2}}} > \frac{12}{8\left(\frac{2\mu_D s}{h+\frac{p-v}{l_c}}\right)^{\frac{1}{2}} - 9\frac{hk}{mpG_u(k)\mu_D}}.$$

To show that (3.9) holds, let us recall the assumption

$$s > \frac{h+\frac{p-v}{l_c}}{\mu_D}, \tag{3.10}$$

which is equivalent to

$$\left(\frac{2\mu_D s}{h+\frac{p-v}{l_c}}\right)^{\frac{1}{2}} > \frac{2}{\left(\frac{2\mu_D s}{h+\frac{p-v}{l_c}}\right)^{\frac{1}{2}}}.$$

At the same time, from (3.2), we have

$$Q^* > \left(\frac{2\mu_D s}{h+\frac{p-v}{l_c}}\right)^{\frac{1}{2}},$$

which proves (3.9) and hence $Q^*(L^*) > Q_0(L^*)$. In other words, the two conditions of the proposition are sufficient to guarantee that (Q^*, L^*), obtained from solving the system in (3.6), falls in the convex region, where $L < L_0(Q), Q > Q_0(L)$, and therefore, is a global minimum for $E[TC_{Q,L}]$. □

The two conditions outlined in Proposition 3 are not very restrictive, because the first one requires $s\mu_D > (h + (p - v)/l_c)$, and the values of μ_D and s are, in reality, much larger than h and $(p - v)/l_c$. Thus, it is easy to assume that the multiplication of the former terms is greater than the summation of the latter terms. Further, for the same reason as well as considering the small values of h and k against large values of p and μ_D, the second condition is also is very likely to be always true under realistic settings.

However, the resulting polynomial from the system in (3.6) cannot be found in closed form to get an explicit definition of the global optimum, (Q^*, L^*), even though it is solvable through a simple numerical search. In the absence of any explicit definition of the optimal solution, we can alternatively use approximations. To do so, we assume that the stockouts are considered as negligible for the optimal order quantity, Q^*. This is a reasonable assumption (for the sake of approximation) because the value of $mp\sigma_D G_u(k)$ is much smaller than s and μ_D, and also the fact that, in reality, lead time is usually less than one year (i.e., $L < 1$) makes this values even smaller, so has a minor impact on the resulting Q^*. Applying this assumption to (3.2), we have an approximately optimal order quantity,

$$\widetilde{Q}^* = \sqrt{\frac{2\mu_D s}{h + \frac{p-v}{l_c}}}. \tag{3.11}$$

Accordingly, substituting $\widetilde{Q}^*$ for Q in (3.4) leads to an an approximately optimal lead time,

$$\widetilde{L}^* = \left[\frac{2w\mu_D}{\left(mpG_u(k)\mu_D\sqrt{\frac{h+\frac{p-v}{l_c}}{2\mu_D s}} + hk\right)\sigma_D}\right]^{\frac{2}{3}}. \tag{3.12}$$

As a result, we have a joint approximately global optimum, $(\widetilde{Q}^*, \widetilde{L}^*)$, which our numerical analysis in the next chapter will show that is a good estimate of the joint exactly global optimum, (Q^*, L^*), for (3.5) and can be defined by (3.11) and (3.12).

Finally, when it comes to analysis of the impact of product characteristics, from (3.12), we can see that demand variability and contribution margin have a negative impact on the optimal lead time, the same observation as we had previously. Equation (3.12) also reveals that product life cycle, l_c, has, however, a positive impact on lead time, meaning that for products with longer life cycle we should set longer lead times. This insight provides further support for Fisher's framework that suggests using efficient supply chains (which usually have long lead times) for functional products (which normally have long life cycles).

3.4 Summary

In this chapter we modeled a two-echelon supply chain in terms of total inventory cost that consists of four major costs, namely, holding, ordering, stockout, and obsolescence. While optimising the model with respect to order quantity and lead time, as the key decisions, we discuss the impact of three product/demand characteristics, namely, demand variability, product life cycle, and contribution margin, on the optimal decisions. Our findings prove that, firstly, the type of product (defined by the given characteristics) influences the choice of supply chain strategy in terms of operational decisions, order quantity and re-order point, level of safety inventory, and duration of lead time. Secondly, the match between product type and supply chain increases the profitability of the firms, while the mismatch leads to (unnecessary) costs of non-optimal strategy, which substantially lowers profit.

Further, expanding on the literature of inventory planning and dual sourcing, we incorporate product life cycle (to formulate obsolescence cost) and variable contribution margin (to formulate stockout cost) into the total supply chain inventory cost model. Single- and bi-variable optimisation of the model with respect to order quantity, lead time, and both is conducted under stochastic demand. In the next chapter the model will be employed for complementary analysis that seeks demonstrating the extent to which our findings support Fisher's (1997) framework.

Chapter 4

Numerical Analysis and Model Extension

In this chapter, we employ the strategy modeled in the previous chapter to continue our exploration of the research objectives in two different ways. First, we conduct a sensitivity analysis that illustrates the impact of the major product/demand characteristics, namely, demand variability, contribution margin, and product life cycle, on the optimal decisions of order quantity and lead time, which imply the supply chain strategy. The analysis is based on some realistic values of the characteristics that result in several scenarios of product type and supply chain strategy. Second, we extend the model to new settings where the supplier operates on a make-to-stock basis rather than make-to-order. This means instead of processing an order only when it is received from the retailer, the supplier now commits to make the product available at a particular level of stock that satisfies demand on a continuous basis.

The objective of the sensitivity analysis is to complement our findings in the previous chapter by making some numerical observations and also demonstrate how the model can be implemented. The extension aims to investigate the impact of the supplier's operating scheme on the supply chain optimal decisions as well as the impact of demand characteristics on the decisions in a different manufacturing environment, i.e., make to stock.

4.1 Numerical Analysis

In this section, we report on a numerical analysis that begins with finding optimal decisions for a given base case scenario. Then, we explore the impact of product/demand characteristics on the optimal decisions. Finally, through a sensitivity analysis, we illustrate how our findings in this paper support the necessity of alignment between product type and supply chain strategy.

4.1.1 Finding Optimal Decisions

The goal of this step is determining the optimal value of the two major decision variables, i.e., order quantity and lead time, in a representative scenario, on which we base our analyses throughout this section. Returning to the supply chain model that was described earlier in Chapter 3, let us suppose (in this representative scenario), for a particular product with $p = 45$, $c = 40$, and $l_c = 4$, annual demand is randomly distributed with $\mu_D = 1000$, and $\sigma_D = 200$. Then, assuming an annual holding cost rate of 30% and a 50% rate at which the unit cost will be retained at the end of life cycle, we have $h = 12$ and $v = 20$. Also, recalling the definition $m = \frac{p-c}{p}$, the profit margin will be $m = 0.1$. The remaining parameters are given as $s = 200$, $w = 0.04$, $k = 1$, $G_u(k) = 0.08$. The logic behind choosing the above values for the parameters in the representative scenario will be discussed later in Section 4.1.3.

Let us consider a case (in the scenario), where lead time is stochastic with mean $\mu_L = 0.15$ and standard deviation $\sigma_L = 0.05$ year, and order quantity is a decision. Following Proposition 3.1, we obtain the optimal order quantity as $Q^* = 161$. Then, considering the case that order quantity is given, e.g., $q = 250$, and the goal is to find the optimal lead time, Proposition 3.2 implies that $L^* = 0.1$.

Turning next to the case of both order size and lead time unknown, we want to find them while they are jointly optimal. According to Proposition 3.3, this requires optimising $E[TC_{Q,L}]$ from (3.5) by solving the two-equation-two-unknown system in (3.6) to get the exact optimal solution, (Q^*, L^*). Alternatively, we can apply (3.11) and (3.12) to determine approximately optimal solution, $(\tilde{Q}^*, \tilde{L}^*)$. The exact solution is $(156, 0.091)$ and the approximate solution is $(148, 0.090)$. The former results in $E[TC_{Q^*,L^*}] = 4023$, while the latter returns $E[TC_{\tilde{Q}^*,\tilde{L}^*}] = 4028$. As claimed earlier in Section 4.3 and is clearly evident here, the alternative approximation provides a very good estimate of the jointly optimal

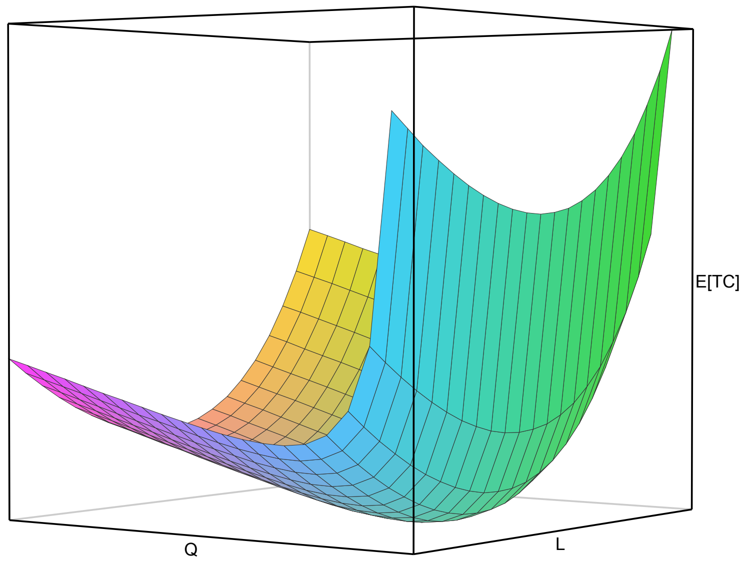

Figure 4.1: Supply chain expected total cost function, $E[TC]$

solution and obviously makes computations faster and easier as compared to solving the two-equation-two-unknown system.

For illustrative purposes, we plot the expected total cost function, $E[TC_{Q,L}]$, in the vicinity of the optimum solution by setting $0 < L < 1$ and $100 < Q < 200$. Figure 4.1 exhibits the output, which confirms the convexity of the function that we analytically proved in the previous section.

4.1.2 Exploring The Impact of Product Characteristics on the Optimal Decisions

In this section, we explore how the optimal supply chain decisions, lead time and order size, are affected by specific product characteristics, demand variability, contribution margin, and product life cycle. The analysis here is based on the representative scenario described in Section 4.1. We, first, assess the impact of product characteristics on the supply chain performance with respect to lead time, then, will see the impact with respect to the order size.

Suppose the supply chain offers the product to multiple (i.e., six) markets which differ only in their demand variability, but are similar in other parameters (i.e., average demand, unit price and costs, etc.) determined previously. The variability of demand ranges from $\sigma_D = 20$ to $\sigma_D = 640$ across the markets. The objective is to see how the optimal level of supply chain responsiveness, measured by lead time, required for each market would vary for one market to another.

The optimal lead time is calculated for all (six) markets and the results are plotted in a line chart as seen in Figure 4.2. The chart shows that optimal lead time decreases (convexly) from nearly 150 days to about 15 days when demand variability increases from 20 units to 640 units (doubled in size from one market to another). Note that in the chart, L^* is in years. Based on the results, the supply chain should operate 37% faster when demand variability doubles in size (and of course, other parameters stay unchanged).

To assess the impact of contribution margin, let us return to the original version of the scenario, and assume that the retailer raises the unit price for the product several times (resulting in price ranging from 45 to 135) to earn higher profit margin. He also manages to keep other parameters unaffected by the price changes (even though it is hardly possible to do so in practice). The optimal lead time corresponding to each new (raised) price is calculated. As Figure 4.2 displays, optimal lead time decreases (almost linearly) from about 150 days to approximately 50 days when price ranges from 45 to 135 (and margin ranges from 0.1 to 0.7). In summary, for a desired profit margin to increase from 10% to 70% (and nothing else changes), the supply chain should be able to quicken its delivery by 67%.

Taking a similar approach, we can explore the impact of product life cycle, provided other parameters remain unchanged. As displayed in Figure 4.2, when the life cycle increases from 6 months to 7 years, the optimal lead time (concavely) increases from 140 days to nearly 160 days. Thus, the shorter the life cycle is, the more responsive the supply chain should be.

As far as the impact of product characteristics on the order quantity is concerned, Equation (3.2) shows that the optimal order size increases in σ_D and m, but decreases in l_c. Further investigations, such as the numerical examples presented above for lead time,

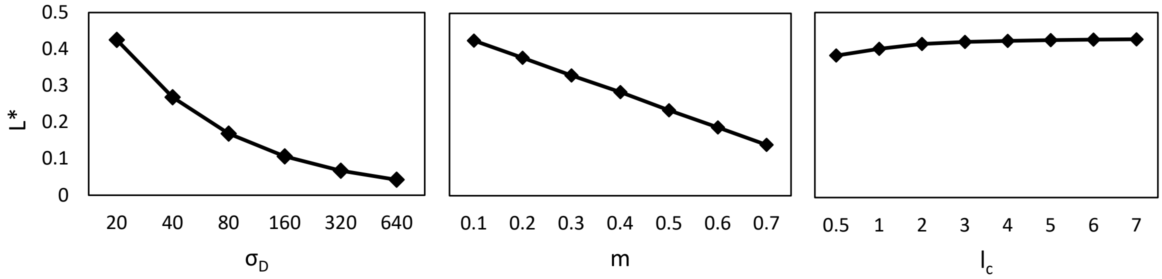

Figure 4.2: The impact of product/demand characteristics on the optimal lead time

can provide a deeper understanding of the quality of the impact. However, this will not be very informative because, theoretically, order size itself is not a good indication of the required supply chain strategy. For this reason, we don't go into a deeper analysis of the impact on the order size. Nevertheless, order quantity can be an initial measure of efficiency that usually aims to achieve leanness by minimising throughput inventory. This requires lowering average inventory, $\frac{Q}{2} + SS$, and therefore, keeping the order size as smaller as possible as long as the total cost doesn't increase. Overall, the product characteristics seem to affect lead time and order quantity in opposite directions, therefore, a best supply chain strategy is the one that effectively matches the characteristics with the decisions, trading off the response time against cost of capacity.

4.1.3 Exploring Alignment between Product Type and Supply Chain Strategy

The focus of this section is on the evaluation of the underlying relationship between the supply chain strategy and the product characteristics by running a set of sensitivity analysis. There are two major considerations here, before we start:

1) When a parameter is changed (to assess its impact on the output), some other parameters that are technically interconnected to that parameter might change too. More specifically, we know that there are several ways to compute the safety factor, k. According to Silver et al. (1998a), for a specified fractional charge per unit, B_2, we have

$$k = F_u^{-1}\left(\frac{Qi}{B_2\mu_D}\right),$$

where F_u^{-1} is the inverse cumulative density of $f(u)$, the standard normal density function. In our formulation of the stockout cost (discussed in Chapter 3), we can show that $B_2 = \frac{m}{1-m}$, so that

$$k = F_u^{-1}\left[\frac{(1-m)Qi}{m\mu_D}\right]. \tag{4.1}$$

This indicates that the safety factor depends on i, m, and μ_D as three product-specific parameters and on Q as a decision that itself depends on other parameters, e.g., l_c. Thus, when, for instance, we change l_c or p (as we did in the previous section), then k and, consequently, $G_u(k)$ are expected to change as well and affect the output. In this section, we consider this effect every time we run the model. To do so, we find k by substituting $\tilde{Q}^*$, acquired from (3.11), for Q in (4.1), and then, find $G_u(k)$ (as was defined in Chapter 3) accordingly.

2) Defining a supply chain strategy is not just finding the right value of lead time and order size, (L^*, Q^*), but requires evaluating other factors such as the required level of safety inventory, and more importantly, considering the expected profit, which is the ultimate goal of all (or most) businesses. For the purpose of our discussion in this section to be more realistic and more informative from a decision making perspective, we describe a supply chain strategy in terms of the five factors, L^*, Q^*, SS, $E[TC]$, and $E[PR]$. The first four factors have been formulated and discussed earlier in the paper and the last one is defined as $E[PR] = p\mu_D - E[TC]$. Evaluation of these factors together provides indications of how the resulting optimal strategy is characterised from several aspects, especially those identified by Fisher (1997), when describing the two fundamental supply chain strategies.

Taking the above-mentioned considerations into account, we run a sensitivity analysis that comprises 13 different scenarios, which illustrate the impact of product characteristics (when they change within particular ranges) on the optimal supply chain strategy. Table 4.1 exhibits the results of the analysis and we discuss them in the following paragraphs.

As is notable, Scenario I is in fact the representative scenario that we based our analysis on in the two previous sub-sections. This scenario presents the specifications of a (relatively extreme case of) functional product with stable demand, small margin, and long life cycle.

Table 4.1: Sensitivity analysis

Scenario	Product characteristics			Supply chain strategy				
	CV	m	lc	Q*	L*	SS	E[TC]	E[PR]
I	0.20	0.10	4.00	148.05	0.10	16.06	1,200.98	43,799.02
II	0.60	0.10	4.00	148.05	0.05	33.41	2,498.13	42,501.87
III	1.00	0.10	4.00	148.05	0.03	46.96	3,511.68	41,488.32
IV	1.40	0.10	4.00	148.05	0.03	58.77	4,394.74	40,605.26
V	0.20	0.20	4.00	143.22	0.08	44.39	1,519.45	48,480.55
VI	0.20	0.40	4.00	129.78	0.06	65.52	1,893.06	65,106.94
VII	0.20	0.60	4.00	111.80	0.05	73.93	2,220.88	97,779.12
VIII	0.20	0.10	2.00	127.78	0.09	24.49	1,272.90	43,727.10
IX	0.20	0.10	1.00	103.98	0.09	34.44	1,364.49	43,635.51
X	0.20	0.10	0.30	64.78	0.08	52.11	1,545.47	43,454.53
XI	0.60	0.20	2.00	121.72	0.04	103.97	3,277.76	46,722.24
XII	1.00	0.40	1.00	82.34	0.02	221.18	5,847.75	61,152.25
XIII	1.40	0.60	0.30	37.89	0.01	339.51	8,794.86	91,205.14

Accordingly, the optimal strategy has a relatively long lead time of 36 days (0.1 year) with a very low safety stock of 16 units. In each of the following scenarios, we expand on the representative scenario by changing the value of one parameter in a particular range while other parameters stay unchanged. In the last three scenarios, the changes occur in multiple parameters at the same time.

In Scenarios II to IV, we assess the impact of demand variability. To create an appropriate measure of variability as well as a reasonable range of change, we apply the quotations given by Cachon and Terwiesch (2009) and Hopp and Spearman (1996). Both references (and nearly the whole body of the operations management literature) believe that coefficient of variations (CV), $\frac{\sigma}{\mu}$, is the best measure of process variability. So, we pick CV as a measure of demand variability. In terms of the range, however, the former suggests that variability is low if CV is less than 0.25, is high if CV is greater than 0.75, and is extremely high if above 1.5. The latter suggest a moderate variability if $0.75 < CV < 1.33$, low variability if less than 0.75, and high variability if above 1.33. We mix these suggestions by creating a range of 0.2 (i.e., very low) to 1.4 (i.e., very high) for the CV. Then, while μ_D is kept at 1000, σ_D increases from 200 to 1400 to produce the range. The output in strategy is clear; L^* decreases (SS increases) to reflect the need for a quicker supply chain (higher safety stock) when uncertainty increases in demand. Further, big growth in total cost and decline in the profit are the effects of increased variability.

Scenarios V to VII demonstrate the impact of profit margin by changing the price so that the margin varies between 10% and 60%. These two numbers come from Fisher's (1997) definition that offers a range of 5% (we rounded it up to 10% to stay in one decimal place) to 20% margin for functional products and a range of 20% to 60% for innovative products. According to Table 1, when m increases from 10% to 60%, both Q^* and L^* decrease (SS increases) to show the need for a more agile supply chain as a result of seeking higher profit margin. Although total cost experiences a slight rise (when m increases), the profit has a significant surge, as would be expected.

Scenarios VIII to X report on the impact of product life cycle when it takes values between 0.3 and 4 years. These values are adopted from Fisher (1997) who believes product life cycle is "between 3 months and 1 year" for innovative products and "more than two years" for functional products. Thus, we set a range of 0.3 (rounded up from 3/12) to 4 (twice more than 2) years for product life cycle. Based on the table, decreasing l_c within this range (from 4 to 0.3) reduces Q^* and L^*, but raises SS, resulting in a small increase in cost and a little lost profit.

Finally, in Scenarios XI to XIII, we observe the impact of all three parameters, CV, m, and l_c, when they change simultaneously. When CV and m increase and l_c decreases all at the same time, the output shows a big drop in Q^* and L^* and large rise in SS as well as a substantial growth in both $E[TC]$ and $E[PR]$. It is notable that parameters in scenario XIII are, in fact, describing an (extreme case of) innovative product, i.e., with volatile demand, large margin, and short life cycle. Interestingly, the resulting strategy in scenario XIII shows the shift towards responsiveness, as compared to scenario I, which describes a(n) (extreme case of) functional product. This clearly confirms the need for alignment between product type and supply chain strategy.

Another interesting observation from the comparison between Scenarios I and XIII lies in the lead times, which are 37 and 5 days, respectively. At the same time, we look at the "lead time required for made-to-order products" that Fisher (1997) expects to be "between 6 months and 1 year" for functional products and "between 1 day and 2 weeks" for innovative products. Although the 37-day lead time does not fall in the expected interval for functional, it is more than 7 times longer than the 5 days for innovative, thereby, long enough to represent a non-responsive supply chain. Furthermore, the expected intervals can be easily met with a simple change in the input, setting $w = 0.5$, for instance, which will return 197 days in Scenario I and 7 days in Scenario XIII, and both fall in the intervals that Fisher (1997) expects.

One may argue that Scenario I and Scenario XIII are not good representatives of the two types of products because any rise in price can easily affect, i.e., reduce, the average demand. The unit cost, c, might be another concern since innovative products are usually expected to have a higher production/procurement cost than functional products (of the same category), and therefore, have higher holding cost rate, h, and shipping cost rate, w, per unit supplied. These concerns are particularly important when some empirical evidence in the literature supports them, see, for example, Harris et al. (2010) in the bicycle industry.

To address the above concerns, we develop a modified version of Scenario XIII and call it Scenario $XIII^M$ where the unit cost is set to 300, thereby, price grows to 750 (to achieve $m = 60\%$). The holding cost and the shipping cost are then $h = 90$ and $w = 0.3$, respectively. We also assume that the rise in the price (from 45 to 750) affects the average demand and drops it (from 1000) to 100 per year with the standard deviation of 140 (to achieve $CV = 1.4$). The resulting optimal strategy for Scenario $XIII^M$ is as follows: $Q^* = 4.38$, $L^* = 0.013$, $SS = 33.14$, $E[TC] = 6,532.76$, and $E[PR] = 68,467.24$. Obviously, this scenario too shows a clear match between innovative product and a responsive supply chain strategy. The match between a functional product and an efficient strategy was also provided by Scenario I, and therefore, we can conclude this section with a strong support to Fisher's (1997) framework.

4.2 Model Extension

In this section we first formulate the extension of the model to a make-to-stock policy and derive the optimal order size, assuming lead time is stochastic. Then, we explore lead-time-based optimality which assumes that order size is pre-determined. Finally, we study joint optimality considering both order quantity and lead time as our decisions.

4.2.1 Optimal Order Quantity

Let us recall the model that we created in the previous chapter. To apply the make-to-stock strategy in the model (instead of the make-to-order that the model is currently based on), we need to assume that the supplier reserves a certain level of capacity in its production/procurement processes. This capacity is required in order to maintain a particular amount of stock at the retailer's site to serve the demand. This stock is different from and additional to the required safety inventory that accommodates variations of demand over lead time. We define the amount of the stock as the average demand over lead time, $\mu_D\mu_L$, and the capacity as the ability to handle orders of size Q in the time frame of μ_L. A holding cost rate of h is charged per unit of product per unit of time (year), so the stock incurs an annual holding cost of $\mu_D\mu_L h$. A unit cost of capacity, a, applies per unit of product readied within a unit of time (year), so the allocated capacity will cost $a\frac{Q}{\mu_L}$. Incorporating these new costs into our original model, presented in (3.1), we have

$$E[\overline{TC}] = \left(\frac{Q}{2} + k\sigma_x + \mu_D\mu_L\right) h + (rQ + s)\frac{\mu_D}{Q} + \frac{Q}{2l_c}(p - v) + a\frac{Q}{\mu_L} + \frac{mp\sigma_x G_u(k)\mu_D}{Q}. \quad (4.2)$$

Following a similar approach as presented in Proposition 3.1, we define the corresponding optimal order quantity as

$$\bar{Q}^* = \sqrt{\frac{2\mu_D(mp\sigma_x G_u(k) + s)}{h + \frac{p-v}{l_c} + \frac{2a}{\mu_L}}}. \quad (4.3)$$

The impact of demand characteristics remains the same as we discussed earlier. Further, lead time and order size still grow in the same direction as $\sigma_x(=\sqrt{\mu_L\sigma_D^2+\mu_D^2\sigma_L^2})$ and $\frac{2a}{\mu_L}$ both lead to an increase in the optimal order size when lead time increases.

4.2.2 Lead-Time-Based Optimality

As in Section 3.2, suppose that the order quantity is pre-determined as q and also $r=\frac{w}{L}$ and $\sigma_x=\sigma_D\sqrt{L}$. The expected total cost in (4.2) is re-formulated with respect to lead time as

$$E[\overline{TC}_L]=(w\mu_D+aq)\frac{1}{L}+\left(\frac{mpG_u(k)\mu_D}{q}+hk\right)\sigma_D\sqrt{L}+h\mu_D L, \tag{4.4}$$

where we removed any term that does not depend on lead time. The function in (4.4) has two new terms, aq and $h\mu_D L$, compared to (3.3) as the result of the new assumptions that we made in the new make-to-stock strategy. Consequently, finding the optimal lead time, $\bar{L}^*$, becomes more difficult because the first derivative of $E[\overline{TC}_L]$ is no longer easily solvable to find the critical point(s), if there are any. Thus, instead, we conduct some analytical investigations about the shape and behaviour of the function, starting with convexity and optimality conditions.

PROPOSITION 4.1 *The expected total cost function $E[\overline{TC}_L]$ has a global minimum, $\bar{L}^*>0$.*

PROOF OF PROPOSITION 4.1

For further simplicity, let's rename $E[\overline{TC}_L]$ as ϕ. From Proposition 3.2, we know that (3.3) is convex in L. Because ϕ differs from (3.3) only by the additional term $h\mu_D L$, which is a (linear) function of L, then ϕ will be convex in L too.

The first and the second derivative of ϕ with respect to L are:

$$\phi'=\frac{d\phi}{dL}=-(w\mu_D+aq)\frac{1}{L^2}+\left(\frac{mpG_u(k)\mu_D}{q}+hk\right)\sigma_D\frac{1}{2\sqrt{L}}+h\mu_D$$

$$\phi''=\frac{d^2\phi}{dL^2}=2(w\mu_D+aq)\frac{1}{L^3}-\left(\frac{mpG_u(k)\mu_D}{q}+hk\right)\sigma_D\frac{1}{4\sqrt{L^3}}.$$

Although the first derivative is not easily solvable to identify potential critical point(s) of ϕ, it is obvious that ϕ' has at least one root within $(0, +\infty)$, because

$$\lim_{L \to 0} \phi' = -\infty$$

$$\lim_{L \to +\infty} \phi' = h\mu_D.$$

The second derivative is, however, solvable and has a (unique) root,

$$\bar{L}_0 = \left[\frac{8(w\mu_D + aq)}{\left(\frac{mpG_u(k)\mu_D}{q} + hk \right) \sigma_D} \right]^{\frac{2}{3}}.$$

This proves that for $0 < L < \bar{L}_0$, we have $\phi'' > 0$, which (not only confirms the convexity of ϕ on this region, but also) indicates that ϕ' is steadily increasing over $(0, \bar{L}_0)$. Substituting $\bar{L}_0$ for L in ϕ' returns

$$\phi'(\bar{L}_0) = \frac{3}{16} \left[\frac{\left(\frac{mpG_u(k)\mu_D}{q} + hk \right)^4}{w\mu_D + aq} \right]^{\frac{1}{3}} + h\mu_D > 0,$$

which confirms that ϕ' increases from $-\infty$ at $L = 0$ to a positive value at $L = \bar{L}_0$. Further, the fact that $\phi'' < 0$ holds for all $L > \bar{L}_0$ and $\lim_{L \to +\infty} \phi' = h\mu_D$ shows that ϕ' stays positive (although decreasing) for all $L > \bar{L}_0$, and approaches $h\mu_D$ when L tends towards $+\infty$. This means that ϕ' crosses the horizontal axis only once at $\bar{L}^*$, and therefore, $\bar{L}^*$ is a global minimum for ϕ. □

To identify the impact of product/demand characteristics on supply chain responsiveness, we now explore how the optimal lead time is affected by changes in these characteristics. The following proposition describes the impact.

PROPOSITION 4.2 *The optimal lead time, $\bar{L}^*$, decreases in demand variability and contribution margin.*

PROOF OF PROPOSITION 4.2

Because there is no explicit formula for $\bar{L}^*$ that directly explains the impact, some further analysis is required. Since it was shown that $\phi^{'} = 0$ at $L = \bar{L}^*$, we can employ the implicit function theorem here for

$$\phi^{'} = -(w\mu_D + aq)\frac{1}{L^2} + \left(\frac{mpG_u(k)\mu_D}{q} + hk\right)\sigma_D \frac{1}{2\sqrt{L}} + h\mu_D = 0.$$

According to the theorem, we have

$$\frac{dL}{d\sigma_D} = -\frac{\frac{d\phi^{'}}{d\sigma_D}}{\frac{d\phi^{'}}{dL}} = -\frac{L}{\frac{4h\mu_D}{\left(\frac{mpG_u(k)\mu_D}{q} + hk\right)} + \frac{3}{2}\sigma_D} < 0$$

and

$$\frac{dL}{dm} = -\frac{\frac{d\phi^{'}}{dm}}{\frac{d\phi^{'}}{dL}} = -\frac{\frac{pG_u(k)\mu_D}{q}\sigma_D L}{4h\mu_D\sqrt{L} + \frac{3}{2}\left(\frac{mpG_u(k)\mu_D}{q} + hk\right)\sigma_D} < 0,$$

which confirm that both demand variability and contribution margin are negatively correlated with the optimal lead time. □

As a result of Proposition 4.2, we understand that the optimal lead time will be shorter when demand has higher variability and/or product has greater contribution margin. In other words, a supply chain needs to operate faster if serving a volatile market and/or delivering a high value product. This insight is consistent with our previous findings in support of Fisher's (1997) framework.

4.2.3 Joint Optimality of Order Quantity and Lead Time

Let us suppose order quantity, Q, and lead time, L, are both decisions to make simultaneously while minimising the expected total cost. This requires jointly optimising the following bi-objective function with respect to Q and L.

$$E[\overline{TC}_{Q,L}] = \frac{w\mu_D}{L} + \frac{s\mu_D}{Q} + \left(h + \frac{p-v}{l_c}\right)\frac{Q}{2} + hk\sigma_D\sqrt{L} + mpG_u(k)\mu_D\sigma_D\frac{\sqrt{L}}{Q} + h\mu_D L + a\frac{Q}{L} \quad (4.5)$$

Proposition 4.3 *The expected total cost function, $E[\overline{TC}_{Q,L}]$ has a global minimum, $(\bar{Q}^*, \bar{L}^*)$, if the conditions outlined in Proposition 3.3 hold.*

Proof of Proposition 4.3

The function in (4.5) is different from (3.5) by the additional term $h\mu_D L + a\frac{Q}{L}$, which is jointly convex in Q and L. Thus, recalling Proposition 3.3, which proves the joint convexity of (3.5) in Q and L, subject to some conditions, we can claim that $E[\overline{TC}_{Q,L}]$ is also jointly convex in the two variables, under the same conditions. Moreover, following the same steps in Proposition 3.3 proves that $(\bar{Q}^*, \bar{L}^*) \in \{L < L_0(Q), Q > Q_0(L)\}$ and, ultimately, the convexity guarantees that $(\bar{Q}^*, \bar{L}^*)$ is a global optimum for $E[\overline{TC}_{Q,L}]$. □

Finding the the global minimum via explicit definition is not possible because $\bar{L}^*$ wasn't explicitly defined. This means that the exact minimum point should be found by numerical search. Nevertheless, having defined $\bar{Q}^*$ in (4.2), we can employ an approximation,

$$\tilde{\bar{Q}}^* = \sqrt{\frac{2\mu_D s}{h + \frac{p-v}{l_c} + \frac{2a}{\mu_L}}}, \quad (4.6)$$

to convert (4.5) into a single-variable function of L, assuming that Q is approximately optimally pre-determined by (4.6) that leads to less complexity in our further analysis.

Substituting $\tilde{\bar{Q}}^*$ for Q in (4.5), we have

$$E[\overline{TC}_{\tilde{\bar{Q}}^*,L}] = \frac{w\mu_D}{L} + \sqrt{\frac{2s\mu_D}{h + \frac{p-v}{l_c} + \frac{2a}{L}}}\frac{a}{L} + h\mu_D L + hk\sigma_D\sqrt{L} + mpG_u(k)\sigma_D\mu_D\sqrt{\frac{L}{2s\mu_D}\left(h + \frac{p-v}{l_c} + \frac{2a}{L}\right)} \quad (4.7)$$

as a new formulation of the expected total cost function with respect to lead time, thus, allows for lead-time-based analysis of the supply chain total cost, while replenishment orders are set in approximately optimal size. This function, however, has a complicated shape that makes finding its critical point(s) difficult. Moreover, because the function is based on approximation, we do not invest in constructing our analysis into propositions and proving them, instead, present our observations in the form of conjectures with some supporting evidence.

CONJECTURE 4.1 *For an approximately optimal order size, $\tilde{\tilde{Q}}^*$, the expected total cost function $E[\overline{TC}_{\tilde{\tilde{Q}}^*,L}]$ has an approximately optimal lead time, $\tilde{\tilde{L}}^* < 1$, if $h > 1$ and the following condition applies*

$$h\left(\frac{k}{2}\sigma_D + \mu_D\right) > w\mu_D + a\sqrt{2s\mu_D}. \tag{4.8}$$

DISCUSSION. For more simplicity, let us start by denoting $E[\overline{TC}_{\tilde{\tilde{Q}}^*,L}]$ as Ω. The first and the second derivative of Ω, after simplification, are as follows:

$$\Omega' = \frac{d\Omega}{dL} = -\frac{w\mu_D}{L^2} + \frac{a^2\sqrt{2s\mu_D}}{\left(h + \frac{p-v}{l_c} + \frac{2a}{L}\right)^{\frac{3}{2}} L^3} - \frac{a\sqrt{2s\mu_D}}{\sqrt{h + \frac{p-v}{l_c} + \frac{2a}{L}}L^2} + \frac{hk\sigma_D}{2\sqrt{L}} + \frac{mpG_u(k)\sigma_D\left(h + \frac{p-v}{l_c}\right)/\sqrt{2s\mu_D}}{2\sqrt{\left(h + \frac{p-v}{l_c} + \frac{2a}{L}\right)L}} + h\mu_D$$

$$\Omega'' = \frac{d^2\Omega}{dL^2} = \frac{2w\mu_D}{L^3} + \frac{3a^3\sqrt{2s\mu_D}}{\left(h + \frac{p-v}{l_c} + \frac{2a}{L}\right)^{\frac{5}{2}} L^5} - \frac{4a^2\sqrt{2s\mu_D}}{\left(h + \frac{p-v}{l_c} + \frac{2a}{L}\right)^{\frac{3}{2}} L^4} + \frac{2a\sqrt{2s\mu_D}}{\sqrt{h + \frac{p-v}{l_c} + \frac{2a}{L}}L^3} - \frac{hk\sigma_D}{4\sqrt{L^3}} - \frac{mpG_u(k)\sigma_D\left(h + \frac{p-v}{l_c}\right)^2/\sqrt{2s\mu_D}}{4\left(h + \frac{p-v}{l_c} + \frac{2a}{L}\right)^{\frac{3}{2}} L^{\frac{3}{2}}}.$$

Considering the conditions

$$\lim_{L\to 0}\Omega' = -\infty$$

$$\lim_{L\to +\infty}\Omega' = h\mu_D,$$

we understand that Ω' has at least one root, $\tilde{\tilde{L}}^*$, that is a (local) minimum for Ω. To prove this analytically, we need to show that $\Omega'(\tilde{\tilde{L}}^*) = 0$ and $\Omega''(\tilde{\tilde{L}}^*) \geq 0$. But it is not easy as $\tilde{\tilde{L}}^*$ is not explicitly known. Let us suppose that $L \geq 1$. Then, working on the Ω' function, we create a lower bound (lwb) for Ω' as

$$lwb = -\frac{w\mu_D}{L^2} - \frac{a\sqrt{2s\mu_D}}{L^2} + \frac{hk\sigma_D}{2\sqrt{L}} + \frac{h\mu_D}{\sqrt{L}},$$

so that

$$\Omega^{'} \geq lwb + \frac{a^2\sqrt{2s\mu_D}}{\left(h + \frac{p-v}{l_c} + \frac{2a}{L}\right)^{\frac{3}{2}} L^3} + \frac{mpG_u(k)\sigma_D\left(h + \frac{p-v}{l_c}\right)}{4s\sqrt{\frac{L}{2s\mu_D}}\left(h + \frac{p-v}{l_c} + \frac{2a}{L}\right)},$$

if $h > 1$. It is obvious that $lwb > 0$, if

$$h\left(\frac{k}{2}\sigma_D + \mu_D\right) > w\mu_D + a\sqrt{2s\mu_D},$$

which is 4.8. Thus, $\Omega^{'} > 0$ for all $L \geq 1$. In other words, if $h > 1$ and (4.8) hold, then Ω has no critical point(s) greater than 1, thereby, $\tilde{\tilde{L}}^* < 1$. However, since it is not easy to show that $\Omega^{''}$ is positive at $\tilde{\tilde{L}}^*$ or definite positive on a range that includes $\tilde{\tilde{L}}^*$, we can not rigorously prove that $\tilde{\tilde{L}}^*$ is a global optimum for Ω. Nevertheless, because $\lim_{L\to 0}\Omega^{''} = +\infty$, and $\tilde{\tilde{L}}^* < 1$, it is very likely that $\Omega^{''}(\tilde{\tilde{L}}^*) \geq 0$. We explored this numerically under several different parameter settings and the outcome shows a support. □

Following on the conjecture above, having $L < 1$ seems reasonable because, a lead time longer than a year will not make sense in reality, unless in very special cases, e.g., aircrafts, ships, one-of-a-kind huge machines, which are easily excluded from this model. Also, assuming $h > 1$ is not too unrealistic since, in practice, the cost of holding an item in stock for a year is greater than one dollar. When this cost is usually estimated to be 30% of the unit production cost, c, then the assumption implies that $c >$ \$3.34, which we can accept for our model. Finally, the condition stated in (4.8) is a sufficient but not necessary because it guarantees the positiveness of a very conservative boundary of for the first derivative of $E[\overline{TC}_{\tilde{\tilde{Q}}^*,L}]$, when $L > 1$. So, there might be some cases where the assumption(s) and/or the condition don't hold, but the approximately optimal lead time, $\tilde{\tilde{L}}^*$, still exists for $E[\overline{TC}_{\tilde{\tilde{Q}}^*,L}]$.

Regarding the impact of product characteristics on the approximately optimal lead time, $\tilde{\tilde{L}}^*$, the conjecture below states how the optimal level of the responsiveness of a supply chain is affected by the characteristics.

CONJECTURE 4.2 *If $a > 1.5$ and $h > 1$, the approximately optimal lead time, $\tilde{\tilde{L}}^*$, decreases in demand variability and contribution margin, but increases in product life cycle.*

DISCUSSION. As discussed earlier in Conjecture 1, $\tilde{\tilde{L}}^*$ is a local minimum for $\Omega = E[\overline{TC}_{\tilde{\tilde{Q}}^*,L}]$, thus, $\Omega' = 0$ and $\Omega'' > 0$ at $L = \tilde{\tilde{L}}^*$. This allows for using the implicit function theorem. According to the theorem, for any $L = \tilde{\tilde{L}}^*$, we have

$$\frac{dL}{d\sigma_D} = -\frac{\dfrac{d\Omega'}{d\sigma_D}}{\dfrac{d\Omega'}{dL}} = -\frac{\dfrac{hk}{2\sqrt{L}} + \dfrac{mpG_u(k)\left(h + \frac{p-v}{l_c}\right)}{4s\sqrt{\frac{L}{2s\mu_D}}\left(h + \frac{p-v}{l_c} + \frac{2a}{L}\right)}}{\omega''(L)} < 0$$

$$\frac{dL}{dm} = -\frac{\dfrac{d\Omega'}{dm}}{\dfrac{d\Omega'}{dL}} = -\frac{\dfrac{pG_u(k)\sigma_D\left(h + \frac{p-v}{l_c}\right)}{4s\sqrt{\frac{L}{2s\mu_D}}\left(h + \frac{p-v}{l_c} + \frac{2a}{L}\right)}}{\omega''(L)} < 0,$$

which clearly prove that the optimal lead time decreases when demand uncertainty and/or profit margin increases. Regarding the impact of product life cycle, the use of theorem suggests

$$\frac{dL}{dl_c} = -\frac{\dfrac{d\Omega'}{dl_c}}{\dfrac{d\Omega'}{dL}} = -\frac{1}{\Omega''(L)}\left(\frac{3a\sqrt{2s\mu_D}(p-v)}{2L^3 l_c^2\left(h + \frac{p-v}{l_c} + \frac{2a}{L}\right)^{\frac{5}{2}}} - \frac{a\sqrt{2s\mu_D}(p-v)}{2L^2 l_c^2\left(h + \frac{p-v}{l_c} + \frac{2a}{L}\right)^{\frac{3}{2}}}\right.$$
$$\left. - \frac{mpG_u(k)\sigma_D(p-v)}{4sl_c^2\sqrt{\frac{L}{2s\mu_D}}\left(h + \frac{p-v}{l_c} + \frac{2a}{L}\right)^{\frac{1}{2}}} + \frac{mpG_u(k)\sigma_D(p-v)(h + \frac{p-v}{l_c})}{8sl_c^2\sqrt{\frac{L}{2s\mu_D}}\left(h + \frac{p-v}{l_c} + \frac{2a}{L}\right)^{\frac{3}{2}}}\right),$$

which is not easy to draw an immediate conclusion on because of the effect of multiple positive and negative terms, and needs a little further investigation. After some rearrangement and simplification, we reach to a new form,

$$\frac{dL}{dl_c} = -\frac{1}{\Omega''(L)} \times \frac{a\sqrt{2s\mu_D}(p-v)}{2L^2 l_c^2 \left(h + \frac{p-v}{l_c} + \frac{2a}{L}\right)^{\frac{3}{2}}} \left[\frac{3}{L\left(h + \frac{p-v}{l_c} + \frac{2a}{L}\right)} - 1\right]$$
$$- \frac{1}{\Omega''(L)} \times \frac{mpG_u(k)\sigma_D(p-v)}{4sl_c^2\sqrt{\frac{L}{2s\mu_D}}\left(h + \frac{p-v}{l_c} + \frac{2a}{L}\right)^{\frac{1}{2}}} \left[-1 + \frac{\left(h + \frac{p-v}{l_c}\right)}{2\left(h + \frac{p-v}{l_c} + \frac{2a}{L}\right)}\right],$$

in which the bracket in the second line is always negative, bearing in mind that $h > 1$ (as well as $L < 1$). The bracket in the first line will also be certainly negative if $a > 1.5$. Then, having the two brackets negative leads to $\frac{dL}{dl_c} > 0$ which indicates that our optimal lead time increases in product life cycle. □

The two assumptions outlined in the conjecture above are not unrealistic because, in practice, the unit cost of production/procurement capacity (a) is much higher than unit holding cost (h). Thus, when $h > 1$, then we can easily assume that $a > 1.5$.

4.3 Summary

In this chapter, we employed the initial model (developed in Chapter 3) to take two further steps towards our research objectives. First, we conducted a set of numerical analysis to explore the impact of product/demand characteristics on the supply chain decisions, and second, we studied an extended scenario where MTS manufacturing policy is implemented by the supplier.

The numerical discussion, which followed by a sensitivity analysis, provided illustrative observations of association between the optimal ordering policy, defined by order quantity and lead time, and particular product-specific characteristics, namely, demand variability, product lifecycle, and contribution margin. Our findings throughout the analysis show support for Fisher's (1997) framework by proving the fact that, firstly, (innovative) products with volatile demand, short life cycle, and high contribution margin, will better match (responsive) supply chains with short lead times. Secondly, implementing the match between the product type and supply chain strategy leads to more profitability and, conversely, a mismatch results in high mismatch costs that decreases the expected profit.

Further, from analyzing the extended scenario we understand that the impact of the product/demand characteristics as well as the effect of the product-supply chain match (and mismatch) remains the same if the manufacturing policy changes from MTO to MTS, while the decisions would differ. This means that our findings are independent of the manufacturing policy and is valid under both MTO and MTS settings.

Chapter 5

Dual Serving Strategies

Aligning supply chain decisions with the characteristics of demand becomes more challenging when facing multiple classes of customers with different purchasing/ordering behaviour. A common example in the retail industry is when a supplier serves its routine individual customers as well as merchants who occasionally show up with large demand. Each of these groups of customers make their purchases according to their needs, resulting in two different patterns of demand. The individuals' demand arrives very often and in small sizes, while the merchants' demand is very irregular and comes in large quantities. At the same time, the former looks easier to manage because of its greater predictability, but the latter can be of higher importance if it constitutes the majority of the sales.

In this chapter, we study this paradoxical situation and how to make right decisions on supply chain design, especially in inventory management. We start by describing the problem and identifying the major issues that arise from an operations management standpoint. Then, with a review of the theoretical background of the research on this problem, we formulate our model to address the issues and explore how findings help decision makers accomplish the alignment of supply and demand.

5.1 Dual Serving Problem

Similar to the dual sourcing problem, where a (local) fast but expensive supplier versus a (remote) slow but cheap supplier are available to source from, here we have a dual serving problem, where a small but frequent demand and a large but sporadic demand exist to serve. Like the dual sourcing problem that seeks a sourcing plan (from the two alternatives) to minimise procurement costs, in the dual serving problem the aim is to find the best serving plan that maximises expected profit. More specifically, we deal with two fundamental questions in a dual serving problem: i) is it worth serving both demands simultaneously or might it be better (in particular circumstances) to ignore one, i.e., the individuals that contribute to a small proportion of sales? ii) when serving both demands, what are the optimal settings of the supply chain strategy? These questions were originally brought to us by a small local firm who was struggling with this precise problem. This chapter aims to address these questions using an analytical approach.

When it comes to practice, the dual serving problem is becoming more common in the retail industry due to the growth of daily deals platforms, where merchants who have purchased a product or service from a manufacturer or a supplier in large quantities to take the advantage of quantity discount, can sell it to individuals at a deal price. An example of such platforms is Groupon. According to Li et al. (2017), the US daily deals industry has grown by 332% over the five years following the launch of Groupon in 2008. Also, in 2016, online retail sales grew at a rate of 15% (Census Bureau 2017), and is predicted to constitute 13% of the US retails sales in 2019 (Forrester Research 2015).

The increasing prevalence of such daily deals platforms leads to more merchants emerging in the online retail market. As a result, more and more suppliers/manufacturers are approached by these merchants to make deals. Dealing with the deals beside the usual individual customers that are served on a daily basis (e.g., via online shopping) forms the dual serving problem. This raises two major issues: i) how to characterise the sporadic and high volume, i.e., lumpy demand of the merchants, and ii) whether/how to dual serve both demands (of individuals and merchants), especially in terms of managing inventories. We discuss these issues in more detail and explore how to deal with them in the next sections.

We address the first issue by developing a model that exogenously explores whether and how the two demands should be jointly served. Supply chain decisions in this model are based on the continuous review and reorder point inventory management. We then address the second issue by investigating the optimal dual serving strategy when decisions are made endogenously based on a protection point inventory. Finally, a numerical discussion complements our analytical results and we conclude the chapter by summarising our findings and discussing some interesting avenues for future research.

5.2 Theoretical Background

The existing literature is rich in some parts of the problem, but is limited in other parts. As far as the characterisation of a lumpy demand is concerned, we have a great amount of research initiated by Feeney and Sherbrooke (1966) who considered a compound Poisson distribution, which assumes Poisson arrivals of customers with batch orders (of constant or random size). Several special cases of the distribution were studied to model the situations where the distribution of the batches is geometric (Adelson 1966, Ward 1978), Bernoulli (Ord 1972), or logarithmic (Sherbrooke 1968, Nahmias and Demmy 1982).

There are two reasons for the popularity and extensive analysis of the compound Poisson in the inventory literature. First, in inventory models, we normally want the cumulative demand to follow a non-decreasing stochastic process with stationary and mutually independent increments. This requirement can be always represented by (a form of) compound Poisson (Axsäter 2015). We know that the case of single unit arrivals forms a special case of pure Poisson. Second, when the intermittent demand pairs with a stochastic lead time that varies over time, finding the distribution of demand over lead time becomes a major concern that can be addressed with more analytical tractability if the demand is (compound) Poisson. For instance, Axsäter (2000) presents the exact analysis of the continuous review policy when demand is compound Poisson. A comprehensive discussion on this is available in Bagchi et al. (1984).

However, there are situations where the inter-arrivals are not exponentially distributed, thus the process cannot be assumed to be (compound) Poisson. In such cases, if the demand per order is one unit, the assumption of normally distributed demand during lead time provides a good approximation, which most of the standard inventory models are based on. However, normality is not a safe assumption for erratic items (Silver et al. 1971). Thus, other approximations, e.g., forms of compound Poisson (Axsäter 2003, Svoronos and Zipkin

1988, Bagchi 1987) or Erlang distribution (Forsberg 1997), should be applied for modeling such lumpy demand.

Sometimes the distribution of arrivals and the batch sizes are either unknown or known but not as common distributions. In such circumstances, the mean and standard deviation of the demand per unit of time can be stochastically determined if the batch sizes are independent of the arrival times (Hees et al. 1972). Also, the distribution of demand over lead time can be approximated, e.g., by normal distribution (Lee and Moinzadeh 1987), if it is not highly skewed and/or the lead time doesn't show high variability; otherwise, the normal distribution provides poor and unusual results (Eppen and Martin 1988). In the ideal conditions, where demand is normal and lead time is constant, an exact normal distribution is formed (Silver et al. 1998b). There are several alternative methods for dealing with non-normal situations where a wide range of other distributions (or distribution-free datasets) can represent demand pattern over lead time. Silver et al. (1998b), Park (2007), and Rossetti and Ünlü (2011) discuss, compare, and evaluate most of these methods.

In terms of the formulation of multiple classes of demand, Veinott (1965) made the first effort by formulating a multi-period single-product system with several demand classes that are independent in each period but not necessarily identically distributed. Most of the studies afterwards focus on developing rationing policies for demand that is classified in terms of the importance/priority of the customers, e.g., based on the shortage cost (Topkis 1968, Ha 1997, Deshpande et al. 2003, Arslan et al. 2007), service level (Guajardo and Rnnqvist 2015, Alfieri et al. 2017), or required flexibility (Nahmias and Demmy 1981, Atan et al. 2018). In this study, we assume demand comprises two classes that are defined based on the distribution/type of customer's orders (arrival and size) and no priority is given to any class.

The prevalence of daily deals platforms is not long; hence, the associated inventory issues have not been widely studied. Alptekinoglu and Tang (2005) consider a retailer who has the choice of opening a direct-serving channel via online shopping and analyse the trade-off between using a depot and using a store to satisfy the (online) demand. Netessine and Rudi (2006) aim to integrate drop-shipping into online retail supply chains by exploring whether the online retailer should hold inventory of particular items or contract with a wholesaler to handle the consumer delivery. Bretthauer et al. (2010) and Mahar et al. (2009a, 2009b) examine, in different settings, a dual-channel retailer to identify the best allocation of online fulfilment centres to each order. Acimovic and Graves (2014) investigate how an online retailer should fulfill each customer's order (i.e., where to ship from, by what shipping method, and how/whether to break down multiple items) to minimise the expected outbound shipping cost. They also analyse how to mitigate demand spillover among the fulfilment centres under a periodic-review joint-replenishment policy (2017), and Lei et al. (2018) provide heuristic methods for approximately optimal joint pricing and fulfilment decisions.

In this chapter, we study a single product inventory problem where a supplier faces two channels of demand, i.e., from individuals, who directly purchase the product online (via the supplier's website), and merchants, who deal in the product by buying large quantities from the supplier and selling them on a daily deals platform. We analyse the problem in two different settings for the inventory policy: i) any demand from either group of customers (merchants or individuals) at any time is served immediately (fully or partly) with as much inventory as we have. A new replenishment order is placed as soon as the reorder level is hit and all unmet demand is lost, or ii) individuals are served immediately at any time, while merchants are only served as long as and as much as inventory on hand remains above a protection level, at which a new replenishment order is placed. Individuals' unmet demand is backlogged and merchants' is lost. Thus, in case (i), decisions are exogenously made regardless of the customer type and inventory level, while in case (ii), decisions are endogenous as we consider both customer group and available inventory when making supply/serving decisions.

5.3 Choice of Serving Strategy

Consider a single product environment in which a supplier has two potential groups of customers, namely, merchants and individuals. The former group place orders of large quantity to the sales office but in a very sporadic fashion, while the latter group purchase small quantities from the website on an almost daily basis. The two groups' demands are independent as they come from very distinct sources. Both the arrivals of the orders and the batches are random and may follow any probability distribution. We denote the distributions of arrivals (in number of times over a period of time, i.e, year) and batches of the orders (in number of units) from merchants by $A^m \sim F_a^m(\mu_a^m, \sigma_a^m)$ and $B^m \sim F_b^m(\mu_b^m, \sigma_b^m)$, respectively, and from the individuals by $A^i \sim F_a^i(\mu_a^i, \sigma_a^i)$ and $B^i \sim F_b^i(\mu_b^i, \sigma_b^i)$. Throughout this chapter, the superscript m refers to merchant and i refers to individual.

In terms of economic parameters, let us suppose that regardless of which customer group an item is going to be sold to, holding one unit per unit of time costs h. Further, placing orders to the manufacturer has a fixed set-up cost s. The selling price, however, is dependent on the order type, denoted as p^m for the merchants and p^i for the individuals. We assume that $p^m \leq p^i$. Both prices are independent of the order size in their demand group, i.e., there is no quantity discount for orders within the merchant or individual group. To stay competitive in the online shopping market, the company offers a free shipping delivery on the items purchased (by individuals) from the website. That means an additional cost per unit, c_p, is incurred for processing individual demand. We assume this cost is added on top of the selling price, p^i, and leads to the offered price, p_o^i, that is displayed on the website for online purchase. Thus, we have $p^i = p_o^i - c_p$.

Due to the continuous (although not regular) arrival of the individuals' demand, we assume the supplier manages its inventory of the product by utilizing a continuous review policy. This means a new order of size Q is placed to the manufacturer any time the inventory position drops to the reorder point, R. The order size is fixed and dictated by the shipping party or decided on the agreement with the supplier. This assumption can be easily relaxed by allowing for EOQ determination if there is no constraint on the order size.

The manufacturer's lead time, l, is constant and is dictated by (or agreed with) the shipping party at the beginning. The reorder point equals the average demand over this time plus a safety stock that accommodates variations of demand. The demand (from any customer) is immediately satisfied in a first come first serve (FCFS) fashion. If the stock is not available, the demand is lost and a lost sales cost is incurred, because the manufacture of the product takes place offshore and takes a long time to fulfil the outstanding orders. Holding inventory and replenishment ordering are the other two main components of the total cost in our model.

In this section, the merchants' demand is assumed to be random in both arrivals and sizes (as described earlier); thus, it is exogenously determined and is independent of the supplier's stock on-hand. In such circumstances, the decision is divided over whether to aggregate demand from both merchants and individuals to serve them simultaneously or to ignore the individual demand because of its very low constitution of total sales. In other words, the concern is whether the revenue earned from the low volume sale of the individual demand trades off the additional cost of uncertainty imposed by increased variance of the aggregated demand. We aim to address the concern by a mathematical model, where the expected total profit is formulated and compared when demand is aggregated as opposed to when it is composed of merchants only.

Let us start formulating our model with the case of both merchants and individuals being served when demand aggregation occurs. According to "the sum of a random number of random variables" probability principle (Ross, 1996, p.22), the mean and standard deviation of the demand per unit of time, D^j, are

$$\mu_D^j = E[D^j] = E[A^j] \times E[B^j] = \mu_a^j \mu_b^j \tag{5.1}$$

and

$$\sigma_D^j = \sqrt{Var[D^j]} = \sqrt{E[A^j] \times Var[B^j] + E[B^j]^2 \times Var[A^j]} = \sqrt{\mu_a^j {\sigma_b^j}^2 + {\mu_b^j}^2 {\sigma_a^j}^2}, \tag{5.2}$$

where, $j \in \{m, i\}$. In the special case where A^j is Poisson distributed, then D^j will have a compound Poisson distribution.

Since the two demands (from the merchants and the individuals) are independent, the aggregated demand,

$$D^g = \sum_{j \in \{m,i\}} D^j,$$

has mean and the standard deviation of

$$\mu_D^g = E[D^g] = E[D^m] + E[D^i] = \mu_D^m + \mu_D^i \tag{5.3}$$

and

$$\sigma_D^g = \sqrt{Var[D^m] + Var[D^i]} = \sqrt{\sigma_D^{m2} + {\sigma_D^i}^2}, \tag{5.4}$$

respectively. Throughout this chapter, the superscript g refers to aggregation.

The expected total inventory cost, which includes holding cost, ordering cost, and lost sales cost, is formulated as

$$E[TC] = \left(\frac{Q}{2} + SS\right) h + \frac{\mu_D^g}{Q} s + (p^g - c)\sigma_x G_u(k) \frac{\mu_D^g}{Q}, \tag{5.5}$$

where, SS is the safety stock, p^g is the weighted average of price under aggregation, σ_x is the standard deviation of demand over lead time, and $G_u(k)$ is a special function that is used for finding the expected shortages per replenishment cycle for a certain value of k, safety factor, which is determined by the management. Following the same principle in the derivation of (5.2) and recalling that the lead time is constant, we define

$$\sigma_x = \sqrt{l}\sigma_D^g. \tag{5.6}$$

Then, the safety stock is $SS = k\sigma_x = k\sqrt{l}\sigma_D^g$. The weighted average price of each unit sold under aggregation is

$$p^g = \frac{\sum_{j \in \{m,i\}} p^j \mu_D^j}{\mu_D^g}. \tag{5.7}$$

Also, according to Silver (1998b), if the demand forecast errors are assumed to be normally distributed, then $\sigma_x G_u(k)$ estimates the amount short per replenishment cycle. Finally, the expected profit is defined by

$$E[\Pi] = \sum_{j \in \{m,i\}} p^j \mu_D^j - E[TC]. \tag{5.8}$$

Having defined the expected profit, we now aim to see whether and in what circumstances the demand aggregation, which means serving both merchants' and individuals' demand simultaneously and on a FCFS discipline, is recommended against serving the merchants only. The following proposition provides the answer.

Proposition 5.1. *Demand aggregation is recommended if*

$$\delta = (p^i - \frac{s}{Q})\mu_D^i + (k^m \sigma_D^m - k^g \sigma_D^g) h \sqrt{l} \\ + [(p^m - c) G_u(k^m) \mu_D^m \sigma_D^m - (p^g - c) G_u(k^g) \mu_D^g \sigma_D^g] \frac{\sqrt{l}}{Q} > 0. \tag{5.9}$$

Proof. Let us denote the expected profit from the merchants' demand only by $E[\Pi^m]$ and the expected profit from the demand aggregation by $E[\Pi^g]$. Then, the additional profit from the inclusion of the individual demand (via aggregation) is

$$\delta = E[\Pi^g] - E[\Pi^m].$$

After applying (5.5) and (5.8) and doing some simplification, we have

$$\delta = \mu_D^i p^i + (SS^m - SS^g)h + (\mu_D^m - \mu_D^g)\frac{s}{Q} + [(p^m - c) G_u(k^m) \mu_D^m \sigma_x^m - (p^g - c) G_u(k^g) \mu_D^g \sigma_x^g] \frac{1}{Q}.$$

As discussed earlier, the assumption of normally distributed demand forecast error (made earlier) and a constant lead time result in $\sigma_x = \sqrt{l}\sigma_D$, which means that

$$SS^m - SS^g = k^m \sigma_x^m - k^g \sigma_x^g = \sqrt{l}(k^m \sigma_D^m - k^g \sigma_D^g).$$

By substituting the above to δ, we have

$$\delta = \mu_D^i \left(p^i - \frac{s}{Q}\right) + (k^m \sigma_D^m - k^g \sigma_D^g)\, h\sqrt{l} \\ + \left[(p^m - c)G_u(k^m)\mu_D^m \sigma_D^m - (p^g - c)G_u(k^g)\mu_D^g \sigma_D^g\right] \frac{\sqrt{l}}{Q}$$

which implies that if $\delta > 0$, the demand aggregation is worth because it would lead to additional profit. □

Considering $k^m < k^g$, $p^m < p^g$, $\mu_D^m < \mu_D^g$, and $\sigma_D^m < \sigma_D^g$, which make the second and the third terms in (5.9) negative, an immediate result from Proposition 5.1 is a necessary condition, $p^i > \frac{s}{Q}$. The condition implies that the selling price to the individual customers must cover the (average) set-up cost per unit shipped from the manufacturer. If the necessary condition is met, then the sufficient condition, in (5.9), is checked.

As far as determining optimal decisions under aggregation is concerned, we can follow the existing rules for a standard continuous review strategy. As we showed in Chapter 3, the optimal order quantity, Q^*, follows (3.2), which results in

$$Q^* = \sqrt{\frac{2\mu_D^g \left((p^g - c)\sigma_D^g G_u(k^g)\sqrt{l} + s\right)}{h}}, \tag{5.10}$$

and the reorder point, R, is defined by

$$R = \mu_D^g l + k^g \sigma_D^g \sqrt{l}. \tag{5.11}$$

Further, according to Chapter 3, if the total cost consists of holding, ordering and stockout (lost sales in this section), then, under optimal settings, the expected total cost of this aggregation strategy will be

$$E[TC(R, Q^*)] = \sqrt{2\mu_D^g \left((p^g - c)\sigma_D^g G_u(k^g)\sqrt{l} + s\right) h} + hk^g \sigma_D^g \sqrt{l}. \tag{5.12}$$

In this section, we first analysed and defined certain conditions under which dual serving through demand aggregation is a right strategy to follow. Then based on the settings of aggregation and using a continuous review system, we defined decisions on order quantity and reorder point, which lead to a minimum expected total cost. In this strategy, we don't incorporate any customer-specific rule/priority nor any inventory level-related consideration while serving the two customers. We use the available stock to serve any demand (of any size) and from any customer at any time on a FCFS basis. When a stockout happens, the whole demand turns to lost sales until a new replenishment order is fulfilled. Although this strategy is simple and easy to implement, it has higher risk of missing both the greater margin from the individuals and the ease of trade with merchants who offer larger batches, because it works on aggregation that almost hides the benefits of these two by averaging (on price and demand). In the next section, we will examine a different strategy that attempts to reduce this risk.

5.4 Optimal Settings of a Dual-Serving Strategy

In this section, we explore the best choice of strategy while simultaneously serving both individuals and merchants. The strategy is defined by decisions that lead to minimum average inventory cost, which is primarily comprised of holding and shortage costs. We work on a particular scenario where the individuals are continuously served and any unmet demand is backlogged. The merchants, however, can only be served if the available inventory is above a certain level, protection level, P, which also limits the amount we can serve a merchant. The inventory under this level is dedicated for individuals' demand over lead time; hence, no merchant's demand is fulfilled during the lead time and will be lost (if it occurs). For further analytical tractability, we assume that the individuals' demand is stable with a constant rate of λ_i and merchants' orders, while consistent in size, b_m, have a Poisson arrival with rate λ_m, which leads to a stochastic time between arrivals, T_m.

A new replenishment order of size Q is placed immediately after serving a merchant's order, if it occurs before individual orders exhaust the inventory above P. The replenishment lead time, l, unit selling price to individuals, p_i, and to merchants, p_m, are constant (with $p_m < p_i$) and the unit production/procurement cost, c, is the same for both customers. Any merchant's unmet demand is lost in full (if occurs within the lead time) or in part (if occurs outside the lead time) at the cost of $p_m - c$ per unit. There is a backorder cost, c_b, charged for each unit short of the individual's demand.

According to the scenario described above, the replenishment cycle repeats either upon a merchant's demand or when the individuals demand gradually lowers the inventory position to the protection level. Similar to any inventory system, the two key decisions here are when to order, i.e., at what value of P, and how much to order, i.e., for what value of Q, to minimise the expected average cost. Since T_m is stochastic and also selling prices to the two groups of the customers are different, finding these decisions is not straightforward. Although both individual demand and lead time are constant and, as a standard continuous review policy suggests, setting P to $l \times \lambda_i$ looks obvious, it is not necessarily an optimal decision. For instance, a lower P might be better if the resulting backlog in individuals' demand is less costly than being held for protection. Similarly, order quantity, Q, varies depending on the best trade-off between the cost of holding inventory and the cost of shortages (either backorders or lost sales). In this section, we explore how to make the decisions while considering these possibilities.

The inventory level has a fixed pattern over time, starting at $P - \lambda_i l$, which is carried over from the previous cycle, and reaching to a maximum of $Q + P - \lambda_i l$, immediately after an order (of size Q) is replenished. Although Q can take any value depending on different factors, demands in particular, for more tractability, we assume that Q is not so large to result in some inventory left above the protection point. This indicates that Q will not be greater than $b_m - \lambda_i l$. Finally, the pattern of inventory level might be different in cycles due to the stochastic nature of merchants' arrivals. As shown in Figure 5.1, two possible cases can happen:

- Case I: $T_m < \frac{Q}{\lambda_i} - l$; A merchant arrives with a batch demand of size b_m while inventory level is above P. In this case, the merchant is served an amount equal to $Q + P - \lambda_i l - \lambda_i T_m$. The remainder of the batch is lost.

- Case II: $T_m \geq \frac{Q}{\lambda_i} - l$; No merchant demand is received and the inventory level decreases to P at the rate of λ_i. In this case, there is no lost sales prior to the protection level.

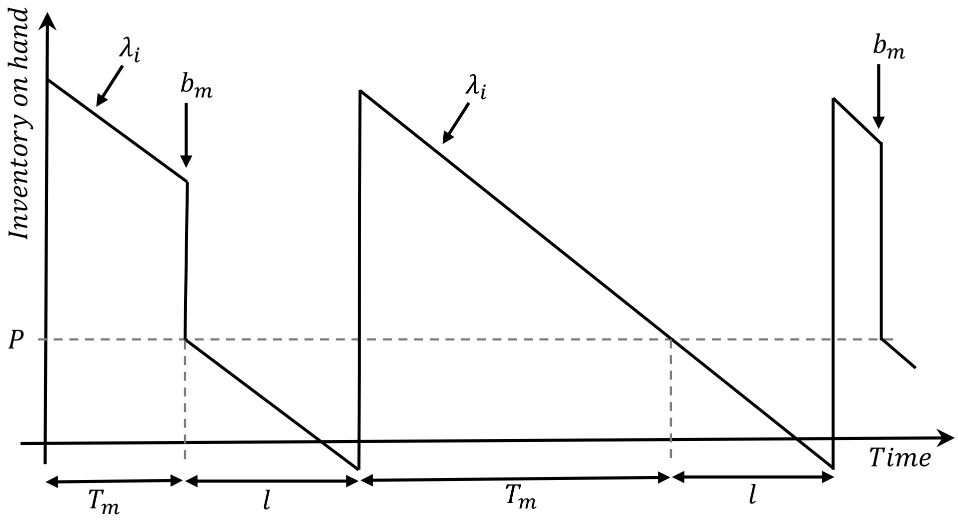

Figure 5.1: Inventory position

As assumed earlier, in both cases, any unmet demand from the merchants and individuals during the lead time is lost and backlogged, respectively. Another major cost that directly depends on the inventory position is holding cost that should trade off with the shortage costs in order to achieve minimum total cost. In the following paragraphs, we define the costs separately and then combine them to formulate the total cost function, which is eventually minimised to achieve the best supply strategy.

5.4.1 Shortage Costs

According to the description of the scenario and the discussion on two different possible cases in the previous section, we anticipate three types of shortage costs that are defined as follows:

1) Cost of lost sales from a merchant's demand that is partially satisfied. The amount of sales that is lost due to a merchant's demand not being fully satisfied is $\kappa_1 = b_m - Q + \lambda_i l + \lambda_i T_m$, which happens in Case I only. Because the merchants' arrivals are Poisson distributed with rate λ_m, the average loss in a cycle is

$$E[\kappa_1] = \int_0^{\frac{Q}{\lambda_i}-l} (b_m - Q + \lambda_i l + \lambda_i t)\lambda_m e^{-\lambda_m t} dt, \tag{5.13}$$

which results in

$$E[\kappa_1] = \left(-b_m - \frac{\lambda_i}{\lambda_m}\right) e^{-\lambda_m\left(\frac{Q}{\lambda_i}-l\right)} + b_m - Q + \lambda_i l + \frac{\lambda_i}{\lambda_m}. \tag{5.14}$$

The associated average cost of lost sales (of this type) is, therefore, $E[\kappa_1](p_m - c)$.

2) Cost of lost sales from missed merchants' demand over lead time. As we assumed for this scenario, merchants are not served during lead time (if they have demand). This leads to some amount of loss, κ_2, that, considering the memoryless property of a Poisson arrival process, is expected to be

$$E[\kappa_2] = b_m \lambda_m l, \tag{5.15}$$

with expected cost of $E[\kappa_2](p_m - c)$ in a cycle.

3) Cost of backlogged demand from individuals, κ_3. If the protection level is less than the expected (individuals') demand over the lead time (to decrease holding cost), some demand is backlogged at the end of the cycle. This shortage only happens if $P \leq \lambda_i l$, and, as shown in Figure 5.2, leads to

$$\kappa_3 = \frac{1}{2}(\lambda_i l - P)\left(l - \frac{P}{\lambda_i}\right), \tag{5.16}$$

which leads to an expected backlogged cost of $\kappa_3 c_b$, where, c_b is the cost charged per unit backlogged. Adding these three cost components together leads to a total expected shortage cost of

$$E[\kappa_1 + \kappa_2](p_m - c) + \kappa_3 c_b \tag{5.17}$$

in a replenishment cycle. If we decide to set $P > \lambda_i l$, then $\kappa_3 = 0$ at the cost of holding some extra inventory. This decision depends on the magnitude of c_b and h, and later, we will discuss it further later.

5.4.2 Holding Cost

The amount of inventory held in this scenario, not only depends on which case for T_m (i.e., I or II) takes place in each cycle, but also varies according to the protection level. We need

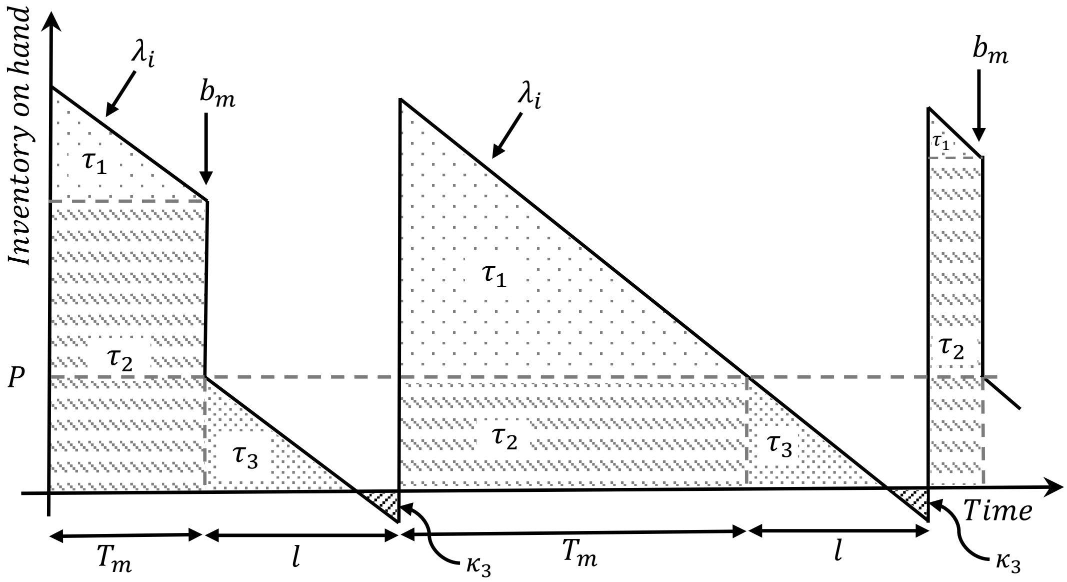

Figure 5.2: Areas of holding inventory and backlogging

to take these conditions into account when estimating the average inventory. We do this in three steps, finding each of the areas (τ_1, τ_2, τ_3) shown in Figure 5.2 in each step.

1) Average inventory prior to reaching the protection level. The amount of inventory held while its level remains above P corresponds to the areas τ_1 and τ_2 in Figure 5.2. However, these are different in Case I and Case II, thus we define them separately for each case. For τ_1, we have

$$\tau_1 = \begin{cases} \frac{1}{2}\lambda_i T_m^2 & ; T_m < \frac{Q}{\lambda_i} - l \\ \frac{1}{2}\lambda_i(\frac{Q}{\lambda_i} - l)^2 & ; T_m \geq \frac{Q}{\lambda_i} - l. \end{cases} \tag{5.18}$$

The expected value of τ_1 in a cycle, is therefore,

$$E[\tau_1] = \int_0^{\frac{Q}{\lambda_i}-l} \frac{1}{2}\lambda_i t^2 \lambda_m e^{-\lambda_m t} dt \; + \; \int_{\frac{Q}{\lambda_i}-l}^{+\infty} \frac{1}{2}\lambda_i \left(\frac{Q}{\lambda_i} - l\right)^2 \lambda_m e^{-\lambda_m t} dt, \tag{5.19}$$

which results in

$$E[\tau_1] = \frac{1}{\lambda_m}\left(\lambda_i l - Q - \frac{\lambda_i}{\lambda_m}\right) e^{-\lambda_m\left(\frac{Q}{\lambda_i} - l\right)} + \frac{\lambda_i}{\lambda_m^2}. \tag{5.20}$$

Similarly, for τ_2, we have

$$\tau_2 = \begin{cases} (Q + P - \lambda_i l - \lambda_i T_m)T_m & ; T_m < \frac{Q}{\lambda_i} - l \\ (\frac{Q}{\lambda_i} - l)P & ; T_m \geq \frac{Q}{\lambda_i} - l. \end{cases} \tag{5.21}$$

Then the expected value of τ_2 in a cycle, is

$$E[\tau_2] = \int_0^{\frac{Q}{\lambda_i} - l} (Q + P - \lambda_i l - \lambda_i t) t \lambda_m e^{-\lambda_m t} dt \; + \; \int_{\frac{Q}{\lambda_i} - l}^{+\infty} \left(\frac{Q}{\lambda_i} - l \right) P \lambda_m e^{-\lambda_m t} dt, \tag{5.22}$$

which results in

$$E[\tau_2] = \frac{1}{\lambda_m} \left(Q - P - \lambda_i l + \frac{2\lambda_i}{\lambda_m} \right) e^{-\lambda_m \left(\frac{Q}{\lambda_i} - l \right)} + \frac{1}{\lambda_m} \left(Q + P - \lambda_i l - \frac{2\lambda_i}{\lambda_m} \right). \tag{5.23}$$

The average inventory per cycle prior to the protection point equals the summation of (5.20) and (5.23), which is

$$E[\tau_1 + \tau_2] = \frac{1}{\lambda_m} \left(-P + \frac{\lambda_i}{\lambda_m} \right) e^{-\lambda_m \left(\frac{Q}{\lambda_i} - l \right)} + \frac{1}{\lambda_m} \left(Q + P - \lambda_i l - \frac{\lambda_i}{\lambda_m} \right). \tag{5.24}$$

2) Average inventory over lead time. The amount of inventory during the lead time is no longer dependent on the stochastic arrival of the merchants, thus as shown in Figure 5.2, the area τ_3 that represents to this amount is the same in both Case I and Case II, and only varies with P. As discussed in the backlog cost, while for a deterministic lead time demand we normally don't expect any stockout, it may be worth (in this scenario) backlogging some demand to save some holding cost. Hence, we can formulate area τ_3 as

$$\tau_3 = \begin{cases} \frac{1}{2}\lambda_i l^2 + (P - \lambda_i l) l & ; P > \lambda_i l \\ \frac{1}{2} P^2 / \lambda_i & ; P \leq \lambda_i l. \end{cases} \tag{5.25}$$

The average total cost of holding inventory in a cycle, when a unit cost of h is incurred per unit of time, would be

$$E[\tau_1 + \tau_2 + \tau_3] h, \tag{5.26}$$

which is determined using (5.24) and (5.25).

5.4.3 Average Total Cost per Unit Time

In this section, we formulate the expected total cost per unit of time. Several expected cost components were defined over each replenishment cycle. The total cost over a cycle will then be the summation of (5.17) and (5.26),

$$E[TC_{cycle}] = E[\tau_1 + \tau_2 + \tau_3]h + E[\kappa_1 + \kappa_2](p_m - c) + E[\kappa_3]c_b. \tag{5.27}$$

Since the cycle length depends on Q, we need an average total cost per unit of time rather than per cycle. This would depend on the length of a cycle, η, which is $T_m + l$ and Q/λ_i for Case I and Case II, respectively, thereby is

$$E[\eta] = \int_0^{\frac{Q}{\lambda_i}-l} (t+l)\lambda_m e^{-\lambda_m t} dt \ + \ \int_{\frac{Q}{\lambda_i}-l}^{+\infty} (Q/\lambda_i)\lambda_m e^{-\lambda_m t} dt, \tag{5.28}$$

which simplifies to

$$E[\eta] = -\frac{1}{\lambda_m} e^{-\lambda_m\left(\frac{Q}{\lambda_i}-l\right)} + l + \frac{1}{\lambda_m}. \tag{5.29}$$

Then, using the renewal reward theorem (Ross, 2010, p. 307), the average total cost per unit of time, $E[TC_t]$, is found as

$$E[TC_t] = \frac{E[TC_{cycle}]}{E[\eta]}. \tag{5.30}$$

5.4.4 Optimal Decisions

Now that the objective function is known in terms of the expected total cost per unit of time, we focus on finding the optimal decisions, starting with the single decision optimization of P. The proposition below explores and outlines the optimality of $E[TC_t]$ with respect to the protection level, P, when the order quantity, Q, is predetermined.

PROPOSITION 5.2. *For a given Q, the optimal level of protection inventory is determined by*

$$P^*(Q) = \frac{\lambda_i}{h + c_b}\left[lc_b - \frac{h}{\lambda_m}\left(1 - e^{-\lambda_m\left(\frac{Q}{\lambda_i}-l\right)}\right)\right], \tag{5.31}$$

which is positive if and only if

$$c_b > \frac{h}{\lambda_m l}\left[1 - e^{-\lambda_m\left(\frac{Q}{\lambda_i} - l\right)}\right].$$

PROOF. From (5.29), we know that $E[\eta]$ is independent of P. Therefore, taking only the relevant terms of $E[TC_{cycle}]$, and ignoring the common terms that are independent of P, we seek to choose P to minimise

$$\begin{cases} \left[l + \frac{1}{\lambda_m}\left(1 - e^{-\lambda_m\left(\frac{Q}{\lambda_i} - l\right)}\right)\right] hP - \frac{1}{2}\lambda_i l^2 h & ; P \geq \lambda_i l \qquad (i) \\ \frac{h + c_b}{2\lambda_i}P^2 - \left[lc_b - \frac{h}{\lambda_m}\left(1 - e^{-\lambda_m\left(\frac{Q}{\lambda_i} - l\right)}\right)\right] P + \frac{1}{2}\lambda_i l^2 c_b & ; P < \lambda_i l \qquad (ii) \end{cases}$$

Now, (i) is clearly increasing in P and hence minimised at $P = \lambda_i l$. Further, (ii) is a quadratic with minimum at P^*, determined by (5.31), but

$$P^* \leq \frac{c_b \lambda_i l}{h + c_b} \leq \lambda_i l.$$

So, P^* must be the optimal value for P, since the cost of (ii) is equal to (i) at $P = \lambda_i l$. □

The condition outlined in Proposition 2 is guaranteed if a sufficient condition,

$$c_b > \frac{h}{\lambda_m l},$$

holds. This condition suggests that the protection level is worth being kept positive, provided that, in the worst case, the cost of backordering one unit of demand (from individuals) over the lead time, lc_b, is higher than holding that until is served to the next merchant, h/λ_m. This intuitively makes sense because otherwise we would better to serve the merchants as much as they need (or we have in-stock inventory) and just bear the shortage cost over lead time.

As far as the optimization with respect to both decisions, P and Q, is concerned, we try to find the optimal value of Q when P is optimally determined using (5.31). This will lead to the total cost per unit of time, $E[TC_t(P,Q)]$, optimized jointly on protection level and order size, (P,Q). The proposition below explains the outcome of the optimization.

PROPOSITION 5.3. *The optimal* (P,Q) *is* $(P^*(b_m-\lambda_i l),(b_m-\lambda_i l))$ *if* $\xi<0$, *where,*

$$\xi = l\lambda_m + \frac{\lambda_i l}{\lambda_m}(3c_b+h+2)+\lambda_i\left(hl^2+\frac{2}{\lambda_m^2}\right)-\frac{(\lambda_i+c_b+1)h}{(h+c_b)^2\lambda_m^2}-(p_m-c)\left(b_m+\frac{\lambda_i}{\lambda_m}\right). \quad (5.32)$$

PROOF. Since the optimal protection level, $P^*(Q)$, is valid for any Q, substituting $P^*(Q)$ for P in (5.30) updates the expected total cost per to $E[TC_t(P^*,Q)]$, which only depends on Q and can be minimised with respect to Q. The cost function is simplified as

$$E[TC_t(P^*,Q)] = \frac{1}{E[\eta]}\left[\alpha e^{-2\lambda_m\left(\frac{Q}{\lambda_i}-l\right)}+\beta e^{-\lambda_m\left(\frac{Q}{\lambda_i}-l\right)}-\frac{2h}{\lambda_m}Qe^{-\lambda_m\left(\frac{Q}{\lambda_i}-l\right)}\right],$$

where,

$$\alpha = \frac{-\lambda_i h^2}{2(h+c_b)\lambda_m^2}$$

and

$$\beta = \frac{3\lambda_i lhc_b}{(h+c_b)\lambda_m}-\frac{(\lambda_i+c_b+1)h}{(h+c_b)^2\lambda_m^2}-\frac{\lambda_i h}{\lambda_m^2}-(p_m-c)(b_m+\frac{\lambda_i}{\lambda_m}),$$

and $E[\eta]$ is defined by (5.29) and depends on Q too. Then, as the first derivative of $E[TC_t(P^*,Q)]$, we have

$$\begin{aligned}\frac{dE[TC_t(P^*,Q)]}{dQ} = \frac{e^{-\lambda_m\left(\frac{Q}{\lambda_i}-l\right)}}{E[\eta]^2}\Bigg[&-\frac{\alpha}{\lambda_i}e^{-2\lambda_m\left(\frac{Q}{\lambda_i}-l\right)}+\frac{2\alpha}{\lambda_i}\left(\frac{\lambda_i}{\lambda_m^2\alpha}-\lambda_m l-1\right)e^{-\lambda_m\left(\frac{Q}{\lambda_i}-l\right)}\\ &-2h\left(l+\frac{1}{\lambda_m}\right)\left(\frac{Q}{\lambda_i}+\frac{1}{\lambda_m}\right)+\frac{1}{\lambda_i}(l\lambda_m+\beta)\Bigg],\end{aligned}$$

which is always negative if

$$\left[-\frac{\alpha}{\lambda_i}e^{-2\lambda_m\left(\frac{Q}{\lambda_i}-l\right)}+\frac{2\alpha}{\lambda_i}\left(\frac{\lambda_i}{\lambda_m^2\alpha}-\lambda_m l-1\right)e^{-\lambda_m\left(\frac{Q}{\lambda_i}-l\right)}\right.$$
$$\left.-2h\left(l+\frac{1}{\lambda_m}\right)\left(\frac{Q}{\lambda_i}+\frac{1}{\lambda_m}\right)+\frac{1}{\lambda_i}(l\lambda_m+\beta)\right]<0,$$

which is equivalent to

$$\frac{\alpha}{\lambda_i}\left[e^{-\lambda_m\left(\frac{Q}{\lambda_i}-l\right)}+\left(\frac{\lambda_i}{\lambda_m^2\alpha}-\lambda_m l-1\right)\right]^2-\frac{\alpha}{\lambda_i}\left(\frac{\lambda_i}{\lambda_m^2\alpha}-\lambda_m l-1\right)^2$$
$$-2h\left(l+\frac{1}{\lambda_m}\right)\left(\frac{Q}{\lambda_i}+\frac{1}{\lambda_m}\right)+\frac{1}{\lambda_i}(l\lambda_m+\beta)<0.$$

This is certainly valid if

$$-\alpha\left(\frac{\lambda_i}{\lambda_m^2\alpha}-\lambda_m l-1\right)^2+l\lambda_m+\beta<0,$$

which, after replacing β and doing some simplifications, results in

$$l\lambda_m+\frac{\lambda_i l}{\lambda_m}(3c_b+h+2)+\lambda_i(hl^2+\frac{2}{\lambda_m^2})-\frac{(\lambda_i+c_b+1)h}{(h+c_b)^2\lambda_m^2}-(p_m-c)\left(b_m+\frac{\lambda_i}{\lambda_m}\right)<0,$$

as outlined in (5.32).

This means, if the condition, $\xi<0$, holds, $E[TC_t(P^*,Q)]$ is decreasing on $Q>0$ and reaches its minimum at the largest possible value of Q, which, as discussed earlier in this section, is equal to $b_m-\lambda_i l$. Therefore, $Q^*=b_m-\lambda_i l$ and $P^*(Q^*)$ jointly minimise the expected total cost per unit of time. □

With the help of Propositions 5.2 and 5.3, we can now set up an optimal dual serving strategy that is defined with two primary decisions, protection level and order quantity. The advantage of this strategy over the one discussed in the previous section is that it distinguishes between the two groups of customers when making decisions. It reduces the detrimental impact of the highly variable demand of the merchants by not serving them during the lead time, while incorporating their large demands in the replenishment order quantity decision. Unlike the previous strategy, that aggregated both demands and served them in a FCFS fashion, this strategy protects the individuals' demand against sudden stockouts caused by merchants' orders and retains their higher margin by backlogging their unmet demand. In the next section, we will compare the two strategies with an illustrative numerical analysis.

However, it might be argued that the comparison between the two strategies can be more rigorous if they are performed on the same operational settings. More specifically, if all unmet demand is lost in one strategy, as we assumed in the previous section, then it should be the case for the other, which we have assumed that allows for individuals' unmet demand to backlog. Thus, despite looking more practical, the backlogging setting for individuals' demand in the protection strategy should be replaced with a lost sales, in order to conduct a more accurate comparative analysis. This replacement, however, results in some changes into our current analysis, because, firstly, stockouts become more costly as the unit cost of lost sales, $p^i - c$, is normally lower than the unit cost of backlogging, c_b. Secondly, the pattern of the inventory position is slightly different. As shown in Figure 5.3, the starting inventory at each cycle is now Q, and not $Q + P - \lambda_i l$ any more, and the inventory on hand is expected to be zero when a new replenishment order is fulfilled. Note that it will never be optimal to set P larger than $\lambda_i l$ as individual orders are deterministic. The following proposition describes the optimal decisions under the new settings of the protection strategy.

Proposition 5.4. *For a given Q, the optimal level of protection inventory (under the lost sales settings) is determined by*

$$P^*(Q) = \min\left\{\frac{\lambda_i}{h}\left[p_i - c - h\left(\frac{Q}{\lambda_i} - l\right)e^{-\lambda_m\left(\frac{Q}{\lambda_i} - l\right)}\right], \lambda_i l\right\} \tag{5.33}$$

and the optimal (P, Q) is $(P^*(b_m), (b_m))$ if

$$p_m > \frac{h}{\lambda_m} + c$$

and

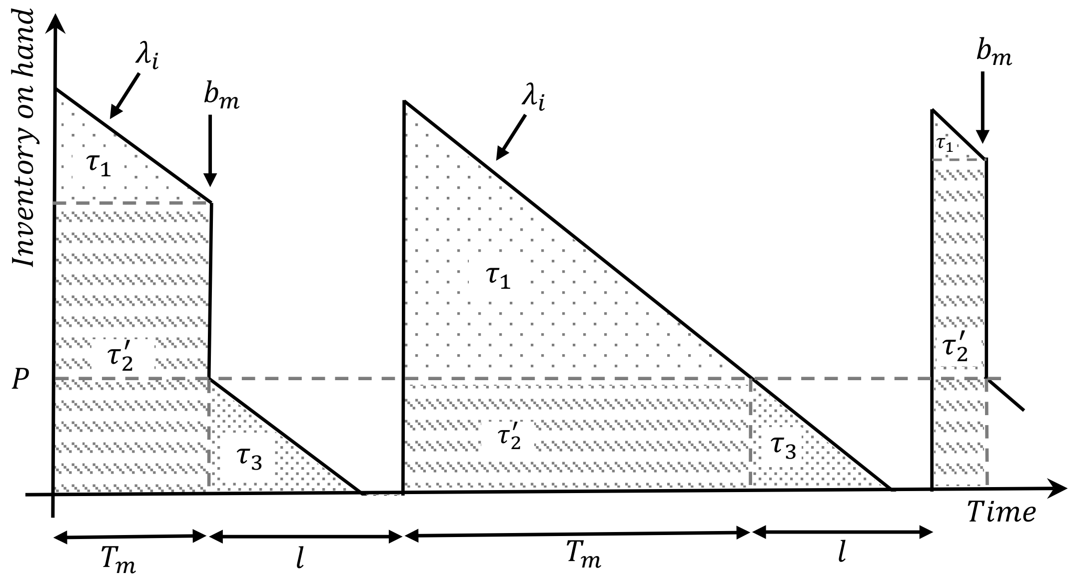

Figure 5.3: Revised areas of holding inventory

$$p_i > \frac{hb_m}{\lambda_i} + c.$$

Proof. As discussed earlier, transforming any individual's unmet demand from a backlog to lost sales changes some shortage costs and some holding costs. More specifically, and as Figure 5.3 details, among three shortage costs described in Section 5.4.1, item 2 remains unchanged, while the first and the third will be updated and defined as follows:

$$E[\kappa_1^{'}] = \int_0^{\frac{Q}{\lambda_i}-l} (b_m - Q + \lambda_i t)\lambda_m e^{-\lambda_m t} dt,$$

which results in

$$E[\kappa_1^{'}] = -\left(b_m + \frac{\lambda_i}{\lambda_m}\right) e^{-\lambda_m\left(\frac{Q}{\lambda_i}-l\right)} + b_m - Q + \frac{\lambda_i}{\lambda_m},$$

and

$$\kappa_3^{'} = \lambda_i l - P.$$

Therefore, the expected total cost of shortage is

$$E[\kappa_1^{'} + \kappa_2](p_m - c) + \kappa_3^{'}(p_i - c).$$

In terms of the holding cost, among the costs discussed in Section 5.4.2, only τ_2 changes as follows:

$$\tau_2^{'} = \begin{cases} (Q - \lambda_i T_m)T_m & ; T_m < \frac{Q}{\lambda_i} - l \\ (\frac{Q}{\lambda_i} - l)P & ; T_m \geq \frac{Q}{\lambda_i} - l. \end{cases}$$

Then the expected value of $\tau_2^{'}$ in a cycle, is

$$E[\tau_2^{'}] = \int_0^{\frac{Q}{\lambda_i}-l} (Q - \lambda_i t)t\lambda_m e^{-\lambda_m t} dt \ + \ \int_{\frac{Q}{\lambda_i}-l}^{+\infty} \left(\frac{Q}{\lambda_i} - l\right) P\lambda_m e^{-\lambda_m t} dt,$$

which results in

$$E[\tau_2^{'}] = \left[\left(\frac{Q}{\lambda_i} - l\right)(P - \lambda_i l) + \frac{1}{\lambda_m}\left(Q - 2\lambda_i l + \frac{2\lambda_i}{\lambda_m}\right)\right] e^{-\lambda_m\left(\frac{Q}{\lambda_i}-l\right)} + \frac{1}{\lambda_m}\left(Q - \frac{2\lambda_i}{\lambda_m}\right).$$

The expected inventory prior to hitting the protection point is then

$$E[\tau_1] + E[\tau_2^{'}] = \left[\left(\frac{Q}{\lambda_i} - l\right)(P - \lambda_i l) + \frac{\lambda_i}{\lambda_m}\left(-l + \frac{1}{\lambda_m}\right)\right] e^{-\lambda_m\left(\frac{Q}{\lambda_i}-l\right)} + \frac{1}{\lambda_m}\left(Q - \frac{\lambda_i}{\lambda_m}\right)$$

and the expected total holding cost in a cycle is, therefore,

$$E[\tau_1 + \tau_2^{'} + \tau_3]h.$$

Since the expected cycle length is the same, the expected total cost per unit of time, $E[TC_t]$, is easily updated. Then following the same approach as we had in Proposition 5.2, we seek to choose P to minimise

$$\begin{cases} \left[l + \left(\frac{Q}{\lambda_i} - l\right) e^{-\lambda_m\left(\frac{Q}{\lambda_i}-l\right)}\right] hP - \frac{1}{2}\lambda_i l^2 h & ; P \geq \lambda_i l \qquad (i) \\ \frac{h}{2\lambda_i}P^2 + \left[h\left(\frac{Q}{\lambda_i} - l\right) e^{-\lambda_m\left(\frac{Q}{\lambda_i}-l\right)} - (p_i - c)\right] P + (p_i - c)\lambda_i l & ; P < \lambda_i l \qquad (ii) \end{cases}$$

Since (i) is increasing in P and (ii) is a quadratic minimised at

$$\frac{\lambda_i}{h}\left[p_i - c - h\left(\frac{Q}{\lambda_i} - l\right)e^{-\lambda_m\left(\frac{Q}{\lambda_i}-l\right)}\right],$$

then, the optimal P is determined by

$$P^*(Q) = \min\left\{\frac{\lambda_i}{h}\left[p_i - c - h\left(\frac{Q}{\lambda_i} - l\right)e^{-\lambda_m\left(\frac{Q}{\lambda_i}-l\right)}\right], \lambda_i l\right\}.$$

Now, $P^*(Q) = \lambda_i l$ because

$$p_i > \frac{hb_m}{\lambda_i} + c,$$

then,

$$\frac{p_i - c}{h} - \frac{b_m}{\lambda_i} \geq 0,$$

then,

$$\frac{p_i - c}{h} - \frac{b_m}{\lambda_i} + l \geq l,$$

then,

$$\frac{\lambda_i(p_i - c)}{h} - b_m + \lambda_i l \geq \lambda_i l,$$

then,

$$\frac{\lambda_i}{h}\left[p_i - c - h\left(\frac{b_m}{\lambda_i} - l\right)\right] \geq \lambda_i l,$$

then, because $Q \leq b_m$, we have

$$\frac{\lambda_i}{h}\left[p_i - c - h\left(\frac{Q}{\lambda_i} - l\right)\right] \geq \lambda_i l,$$

then, because $e^{-\lambda_m\left(\frac{Q}{\lambda_i}-l\right)} < 1$, we have

$$\frac{\lambda_i}{h}\left[p_i - c - h\left(\frac{Q}{\lambda_i} - l\right)e^{-\lambda_m\left(\frac{Q}{\lambda_i}-l\right)}\right] \geq \lambda_i l,$$

which means that optimal P is at $\lambda_i l$.

Now, for the optimization with respect to Q, when $P = \lambda_i l$ and only terms that are dependant on Q are taken, we have (from (5.30))

$$E[TC_t] = \frac{1}{E[\eta]}\left[\gamma e^{-\lambda_m\left(\frac{Q}{\lambda_i}-l\right)} + \omega Q\right],$$

where,

$$\gamma = \left(b_m + \frac{\lambda_i}{\lambda_m}\right)(p_m - c) + \frac{\lambda_i}{\lambda_m}\left(-l + \frac{1}{\lambda_m}\right)h$$

and

$$\omega = \left(\frac{h}{\lambda_m} - p_m + c\right).$$

Then, the first derivative of $E[TC_t]$,

$$\frac{dE[TC_t]}{dQ} = \frac{-1}{E[\eta]^2}\left[\frac{\gamma}{\lambda_i}(l\lambda_m + 1) + \left(\frac{1}{\lambda_m} + \frac{Q}{\lambda_i}\right)\omega\right]e^{-\lambda_m\left(\frac{Q}{\lambda_i}-l\right)} + \frac{1}{E[\eta]^2}\left(l + \frac{1}{\lambda_m}\right)\omega,$$

is always negative, if $\omega < 0$, which is true when

$$\frac{h}{\lambda_m} - p_m + c < 0,$$

and indicates that $E[TC_t]$ is decreasing on $Q > 0$ to be minimised at the maximum possible value of Q, which is b_m (by assumption). □

5.5 Numerical Analysis

In this section, we conduct a numerical analysis to compare the two dual serving strategies that we discussed in this chapter. The first strategy, which we studied in Section 5.3, and herein call the aggregation strategy, combines demand from the two customer segments, individuals and merchants, and employs a continuous review system to serve both simultaneously, provided that a certain condition holds to ensure dual serving is the right choice. The combined demand is continuously fulfilled and if a stockout happens, any unmet demand is lost. The second strategy, which we studied in Section 5.4, and herein call the protection strategy, deals with the two customers differently. It serves the merchants so long as the inventory on hand remains above a certain level (which may also lead to an order being partially satisfied until the protection level), while constantly satisfies individuals' demand until available stock drops to zero. Throughout this section we assume that, in both strategies, any unmet demand from merchants or individuals is lost.

Let us first translate the expressions used in Section 5.3 to what we had in Section 5.4, so that we have a common notation by which the decisions in both strategies are defined. Recalling Equations (5.1) to (5.4) and (5.6) and (5.7), we have

$$\mu_D^i = \lambda_i \ , \ \mu_D^m = b_m \lambda_m$$

$$\sigma_D^i = 0 \ , \ \sigma_D^m = b_m \lambda_m$$

$$\mu_D^g = \lambda_i + b_m \lambda_m$$

$$\sigma_D^g = b_m \lambda_m$$

$$\sigma_x = \sigma_D^g \sqrt{l}$$

$$p^g = \frac{p^i \lambda_i + p^m b_m \lambda_m}{\lambda_i + b_m \lambda_m},$$

which allow us to define the optimal order quantity, Q^*_{agg}, reorder point, R, and the expected total cost, $E[TC(R, Q^*_{agg}]$, using (5.10), (5.11), and (5.12), respectively, as follows:

$$Q^* = \sqrt{\frac{2(\lambda_i + b_m \lambda_m) \left[(p^g - c)(b_m \lambda_m) G_u(k^g)\sqrt{l} + s\right]}{h}}, \tag{5.34}$$

$$R = (\lambda_i + b_m \lambda_m) l + b_m \lambda_m k^g \sqrt{l}, \tag{5.35}$$

$$E[TC(R, Q^*_{agg})] = \sqrt{2(\lambda_i + b_m \lambda_m) \left[(p^g - c)(b_m \lambda_m) G_u(k^g)\sqrt{l} + s\right] h} + h k^g b_m \lambda_m \sqrt{l}, \tag{5.36}$$

where, k^g and $G_u(k^g)$ are determined in the same way we explained earlier in Chapter 4.

Now we describe details of a dataset from a real business, which, as mentioned earlier at the beginning of this chapter, is a local firm whose owner brought the dual serving problem to us seeking help with finding a solution. This was the initial motivation of dealing with the problem in this research. For confidentiality reasons, here we anonymously use their data (with some minor modifications such as rounding) that belongs to a single model of the whole product family that they offer. The company sells the product online at the price of $p^i = \$60$. The demand from individual shoppers is almost stable at about 4 units per day. Although in practice, it changes over time, to comply with our model, we assume that it is constant with the annual rate of $\lambda_i = 1460$. They also have some occasional orders that are very big in size, i.e., $b_m = 400$, but occur rarely, about once a month, and completely randomly across a year, thus, it is safe to assume that they follow a Poisson distribution with average $\lambda_m = 12$ per year. We were not given data on the merchant's price because of confidentiality. Here we assume that these big orders can benefit from a significant quantity discount by being offered a price of $p^m = \$40$. The procurement cost for the firm comprises a unit cost of $c = \$35$ per item and (since we were not also given data on fixed costs, we assume) a fixed cost of $s = \$200$ per replenishment order. An annual holding cost rate of $i = 10\%$ is applied to each unit. All stockouts will turn to lost sales, thereby, the margin is lost. The replenishment orders are expected to take about 20 days to be delivered and are consistent at this time frame.

Now we explore the optimal settings of each strategy for the the above case. After checking all necessary conditions, outlined in Propositions 5.1, 5.2, and 5.4, the aggregation strategy is defined by (5.34) to (5.36) and the protection strategy (with the lost sales settings) is defined by (5.33) and Table 5.1 summarises the results. As it is clear from the table, the aggregation strategy performs better under the current settings. When we look at the cost break down of the protection strategy, it is obvious (and expected) that cost of lost sales from missed merchants' demand over the lead time makes up a very large part of the total cost. This very large cost is incurred for the favour of creating more security of sales to individuals, thus, if, for example, the selling price to merchants drops by only \$2, the protection strategy becomes cheaper, as Table 5.2 details.

Moreover, as the values of order quantity and protection/reorder level demonstrate (in both tables), the protection strategy looks more lean with very low average inventory, but at the high risk of lost sales, whereas, the aggregation strategy invests more in maintaining high (supply) capacity to serve both demands as soon as they arrive. It is evident that if cost of carrying inventory changes, e.g., from \$3 to \$17.5 (by gradually increasing i from 10% to 50%), the aggregation strategy will quickly lose the competition, as illustrated by Figure 5.4. The reason is that the cost of money tied up with the inventory held goes up rapidly and increases the total cost, which is higher in aggregation because of its higher average inventory.

Another interesting observation from Figure 5.4 is that the protection strategy is not very reactive to the changes of the unit holding cost and its total cost grows very slowly. This is of course because the decisions in this strategy are independent of the holding cost, but another underlying factor is the fact that it performs on a very low inventory and therefore, changes of holding cost settings are not amplified with the increasing level of stock.

A completely opposite impact is observed from the unit margin, even though either of the decisions is not dependant on it. If, for example, the unit selling price to merchants increases gradually from \$40 to \$60, as Figure 5.5 shows, the total cost of aggregation grows slowly, while of the protection increases much faster. This is indeed due to the high amount of lost sales from the merchants. This observation intuitively makes sense because, as we proved earlier in this study, efficient/lean supply chains are not a right choice for innovative products.

5.6 Summary

In this chapter, we studied supply chain decisions in a dual serving problem, where a routine, low volume, but frequent demand as well as a large but sporadic demand both exist for a particular product and the supplier needs to decide whether and how to serve

Table 5.1: Comparison between two strategies

Strategy	Aggregation	Protection
Order quantity	2,727	400
Reorder/Protection level	1,095	88
Total cost	12,064	15,623

Table 5.2: Comparison between two strategies with a drop in selling price

Strategy	Aggregation	Protection
Order quantity	2,524	400
Reorder/Protection level	1,095	88
Total cost	11,353	10,224

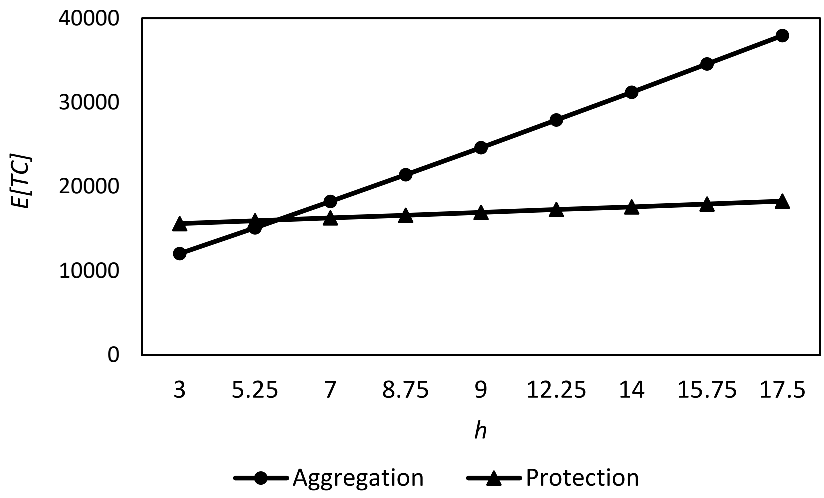

Figure 5.4: The impact of unit holding cost

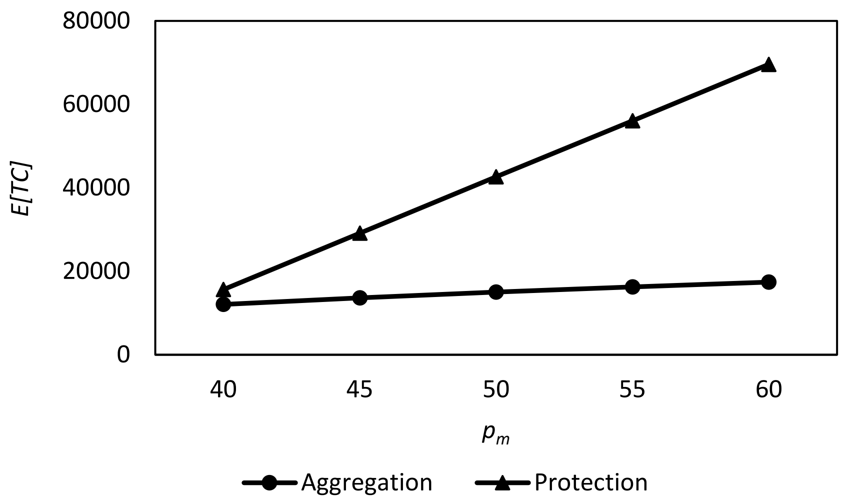

Figure 5.5: The impact of selling price (margin)

them simultaneously. Between these two types of demand, the former is more stable and predictable, therefore, easier to manage, but the revenue earned from this demand is low because of its low volume. On the other hand, the latter is lumpy and difficult to forecast, but it accounts for a large proportion of sales, thus is more attractive to yield revenue. This paradoxical situation raises the concern that it might be better (in particular circumstances) to ignore one demand, i.e., the individuals that contribute to a small proportion of sales. Moreover, if it turns out to be worth jointly serving both demands, the very different nature of these two (which require different settings of supply strategy) leads to another concern, namely, how to design the best dual serving strategy. These concerns were initially brought to our attention by a local firm who has been facing the dual serving problem that we aimed to address in this chapter.

We explored the problem from two angles: i) Dealing with the first concern, we analysed the circumstances in which joint serving is the correct choice and how its optimal design should be. We formulated the problem based on the continuous review system and the aggregated demand from individuals and merchants. In this formulation, any observed demand is served immediately until reaching zero stock, which leads to lost sales until the new replenishment order is fulfilled. ii) Addressing the second concern, we analysed a protection strategy, where, individuals are served constantly, while merchants are served if and until stock on hand stays above a certain protection level. Any unmet demand from the former group is backlogged (or lost) and from the latter group is lost. Using a numerical example, we eventually, compared the two cases, demand aggregation and protection level, to see which one is more cost effective.

Our results show that, in the dual serving problem, not only jointly supplying both demands is reasonable only under certain conditions (that we explicitly outlined in this study), but also, that the optimal choice and design of a dual serving strategy substantially varies according to several factors, including, comparative characteristics of both demands, economic parameters, and product type, i.e., value-adding capacity. For example, we observed that, in a particular representative scenario, while the aggregation strategy was a better choice (over the protection), a small rise in the holding cost rate immediately resulted in the protection strategy significantly outperforming aggregation strategy.

Overall, it is evident that the aggregation strategy, which invests in building high supply capacity through a large safety inventory and relatively big replenishment order sizes, performs better when variability of demand and/or profit margin are higher. In contrast, the protection strategy, which is more lean and maintains a much lower inventory level, is more efficient when greater money is tied up with inventory, i.e., when the unit procurement cost or the holding cost rate is high.

Chapter 6

Conclusions

At this final stage of the study, we briefly review the major steps taken towards the objective of the research. We then highlight our key findings in response to the initial research questions and discuss how they contribute to the literature. Finally, the limitations of this research as well as the potential directions for the future research will be discussed.

6.1 Contribution Remarks and Discussion

A traditionally accepted concept, which has been supported by a great deal of evidence, suggests that firms should design their supply chain strategies in alignment with their product/demand characteristics. One of the most well-known formulations of this alignment was presented by Fisher (1997), who developed a strategy framework that matches functional and innovative products with efficient and responsive supply chains, respectively. Despite a substantial number of works that implemented or extended the framework over the last two decades, the literature has not yet reached a consensus on the validity of the framework and we have some non-supporting evidence against it.

A review of the literature shows that the framework is facing five major concerns, which believe that: 1) insufficient supply chain strategies are offered, as the framework recognises only physically efficient and market responsive strategies, while other alternatives, such as "physically responsive" or "hybrid solution" exist, 2) insufficient number of factors are used for characterising product types, while additional factors such as value-adding capacity, uniqueness, complexity of design, market growth rate, etc. can help with a more precise classification, 3) operationalisation of the theory is not clearly instructed in a way so that practitioners know how to implement the right strategy, 4) generalisability of the framework is questionable when it is aimed to be used is specific sectors, such as agriculture and food, which have unique features, e.g., food safety, biological variations, perishability, etc., and 5) lack of strong analytical support and broad empirical endorsement challenges the capability of the framework in providing adequate strategic guidance.

Addressing the last concern was the initial driver of this study to provide an analytical validation for the framework and explore the extent to which our findings support Fisher's (1997) proposition on supply chain strategy. We based our analysis on a two-echelon supply chain structure (composed of a supplier/manufacturer and a retailer) and developed an inventory model that consists of four major costs, namely, holding, ordering, stockout, and obsolescence. While optimising the model with respect to order quantity and lead time, as the key decisions, we discussed the impact of three primary product/demand characteristics, namely, demand variability, product life cycle, and contribution margin, on the optimal decisions.

Our findings proved that, firstly, the type of product (defined by the given characteristics) influences the choice of supply chain strategy in terms of operational decisions, order quantity and re-order point, level of safety inventory, and the length of lead time. More specifically, an innovative product (as compared with a functional product) would require a smaller order quantity, a greater reorder point, and a shorter lead time, and in other words, a more responsive supply chain. Secondly, the match between product type and supply chain increases the profitability of the firms, while the mismatch leads to (unnecessary) costs of a non-optimal strategy, which substantially lowers expected profit.

While conducting the supply-product match analysis, we made a further contribution that expands on the literature of inventory planning and the dual sourcing problem, by incorporating product life cycle (to formulate obsolescence cost) and variable contribution margin (to formulate stockout cost) into the total supply chain inventory cost model. Single- and bi-variable optimisation of the model with respect to order quantity, lead time, and both was carried out under stochastic demand. Both make-to-order (MTO) and make-to-stock (MTS) settings were analysed (in Chapters 3 and 4, respectively). These analytical findings were then complemented by a numerical discussion of a sensitivity analysis that provided illustrative observations of the optimal ordering policy and the product-specific influencing characteristics. The observations demonstrated that when the product type shifts from functional to innovative (by carefully changing particular settings of the characteristics, which all come from the literature), the corresponding optimal supply chain strategy shifts from being efficient to responsive.

We then focussed on a particular problem (of matching supply strategy with demand characteristics), i.e., dual serving, that is becoming increasingly important in the retail industry, especially in the online daily deals platforms. We investigated whether and in what circumstances a supplier should simultaneously serve both individuals, who have low but stable demand, and merchants, who have large but sporadic demand. Also, if the joint serving is worthwhile, then we studied how the best dual serving strategy should be designed. We investigated the problem under two different settings, where decisions are made exogenously and based on the aggregated demand, which we called aggregation strategy, or endogenously and according to a particular protection level that limits the supply to the merchants, which we called the protection strategy.

Our analysis of the dual serving problem showed that, under either of the settings, both classes of demand are better to be served as long as certain conditions hold. However, each strategy outperforms the other in particular situations that vary in terms of demand characteristics, e.g., variability and volume, and/or economic parameters, e.g., holding and procurement cost. More specifically, we observed that the aggregation strategy, which is more responsive because it reserves high supply capacity to immediately fulfil any demand, is a better choice when demand is volatile and/or holding cost is low and/or average contribution margin is high. In contrast, the protection strategy, which is more lean and physically efficient because risks losing some of (lumpy) demand to lower required supply of inventory, works better (than the aggregation) on a stable demand and/or high holding cost and/or low contribution margin. This observation is not only a contribution to the dual serving literature, but also, consistent with our previous findings on how to match supply strategy with product/demand characteristics.

6.2 Answering Research Questions

We summarise our contribution to the literature by revisiting the initial research questions (outlined in the first chapter) and presenting our findings in clear and concise answers:

1. How does the literature of supply chain reflect on Fisher's framework over the last two decades?

    - The reflection of the literature on the framework includes conceptual extensions, which suggest complementary dimensions/characteristics, empirical applications, whose results are very inconsistent ranging from a full support to a full rejection, and mathematical evaluations, which partially support the framework but in a limited capacity.

2. Can we provide an analytical support for Fisher's framework? And, in general, how does the (right) choice of supply chain strategy change when demand/product characteristics change?

    - Based on the mathematical formulation and optimisation of a two-echelon supply chain model, we proved that not only the type of product/demand has a significant impact on the choice of supply chain strategy (and its corresponding optimal decisions), but also matching the strategy with product type improves overall profitability (which is a clear support for the framework).

3. What will be the right choice (and the optimal settings) of strategy for the dual serving problem from the lens of demand characteristics?

    - Dealing with the dual serving problem, we mathematically explored two particular strategies, aggregation and protection, and our findings show that the aggregation strategy, which invests in building high supply capacity (e.g., buffer stock and replenishment order), performs better when variability of demand and/or profit margin are higher. In contrast, the protection, which is a lean strategy that maintains very low inventory level, works better when the money tied up with inventory (e.g., unit procurement cost or holding cost rate) is high.

6.3 Managerial Implications

Apart from answering specific research questions as discussed above, the findings of this study provide some new practical insights into the way managers make decisions on supply chain design and strategy. Although we discussed these insights separately earlier in several places of this report, it is worth summarising them here too. We discuss the managerial implications of this research in two different decision levels, i.e., strategic and operational.

At the strategic level, managers need to create and maintain an alignment between the design of their supply chain and the type of product. In general, the former comes into two entirely distinct forms, namely, efficient (or lean) and responsive (or agile), and the latter exists in two different types of functional (or commodity-type) and innovative (or fashionable). Functional products need efficient supply chains and innovative products need responsive supply chains. It is essential that managers understand and establish this matching paradigm. There are guidelines for designing supply chains as well as characteristics for identifying product types. As a result, for different sets of product/demand characteristics, different decisions needed to create a right supply chain strategy.

When it comes to the operational level, demand uncertainty, life cycle, and contribution margin, as three (but not only) determinants of product type, should match the lead time and safety inventory as two (but not only) key decisions on supply chain design. More specifically, when a product has a volatile demand, short life cycle, and large contribution margin (i.e., is innovative), we need a short lead time and excess safety inventory (i.e., responsive supply chain). If the characteristics of product are at opposite settings, namely, stable demand, long life cycle, and small contribution (i.e., functional product), we can allow for a long lead time and low safety stock (i.e., efficient supply chain). A firm can have both types of products at the same time, but it must also have both supply chain strategies in place too in order to achieve the strategic alignment and, therefore, save a lot of operational cost, gain competitiveness, and increase its profitability.

In a particular situation of dual serving problem, which is increasingly becoming popular in retail industry, the strategic alignment can be translated into specific settings that may result in either aggregation or protection strategies of inventory management. The former is more responsive and helps more effectively when the demand is very lumpy and unpredictable, while the latter is more efficient and works better when demand has some degree of predictability. An operations manager can set up each strategy at its optimal level if certain conditions hold and sufficient information is available for making the optimal decisions.

6.4 Limitations and Suggestions

This study, despite the abovementioned contributions, has its own limitations, which in turn call for further research and analysis in several ways. Similar to any modelling work, the assumptions that we make in order to formulate the problem, are, in fact, the main limitations. However, some assumptions are very common because they are not too unrealistic. For instance, assuming that a retailer adopts a continuous review for inventory control is not too far from reality, thus, while it limits the output of the model to cases where this assumption is in place, it still applies to many real world cases. On the other hand, we have some assumptions that may look unrealistic, e.g., the unit price of the product being constant over the life cycle or individuals' demand being constant over time. Nevertheless, the output can be significantly helpful as it provides a good intuition of the potential output and/or indication of valid start point for further analysis.

In this research, we have a combination of both realistic and unrealistic assumptions that we discussed in detail earlier. Relaxation of any of these assumptions can be a potential extension to this study to open new avenues for future research. In the following paragraphs, we suggest some of these extensions that, from our view, are most beneficial to expand on the literature.

Regarding the validation of the supply chain-product type framework, we suggest: 1) Including other product characteristics that are normally considered, e.g., product variety and complexity, market growth rate, substitutability, time to market, and assembly lead time, and/or additional alternative supply chain strategies, e.g., risk-hedging and physically responsive; 2) Expanding the supply chain structure to more than two echelons, e.g., by adding a distributor/wholesaler; 3) Considering the impact of competition among the suppliers, and/or in the market; and 4) Incorporating the role of information sharing and collaboration among the partners of the supply chain.

With respect to the dual serving problem, we suggest: 1) Relaxing some simplifying assumptions, such as individuals' deterministic demand and merchants' order size and Poisson arrivals in the protection strategy, and deterministic lead time in both strategies. 2) Allowing for backlogging option besides the lost sales for both individuals and merchants; and 3) Looking at the impact of product variety.

In terms of the modelling practices, our work encourages future research to consider: 1) Formulating demand under variable/stochastic product life cycle, price-sensitive customers, and/or non-normally distributed forecast errors; 2) Incorporating other effects of stockout, such as a change in the customer's next purchase decision (and future demand), loss of the retailer's reputation, cannibalization of the sale from other products with higher margin (due to an offered promotion), and the possibility of strategic out-of-stocks; 3) Applying other production/inventory settings, e.g., periodic-review systems, order crossovers, and product returns; and 4) Modelling a decentralised problem, where, for instance, a two-stage game allows for different decisions to be made separately by a retailer and a supplier while they aim to maximise their profit.

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