

DEVELOPING SUPPLY CHAIN AGILITY FOR THE HIGH-VOLUME AND HIGH-VARIETY INDUSTRY

A Dissertation Presented for the

Doctor of Philosophy

Degree

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DEDICATION

This dissertation is dedicated to my late mother, who very regrettably, cannot see me graduate. The dedication is also shared by my beloved wife, Netsi; daughter, Ephrata; and son, Mathew for their love and understandings. I love you all!

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First and above all, I am thankful to Almighty God for His unconditional love, forgiveness, and blessings. “I am the vine; you are the branches. He who abides in Me, and I in him, bears much fruit; for without Me, you can do nothing” (John 15:5, New International Version).

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ABSTRACT

Supply chains are under pressure to meet performance expectations under conditions in which access to the global network of suppliers and customers is fluid. Most studies accept the importance of agility to enhance performance using flexibility as a key dimension. Moreover, based on literature and empirical implications, it is essentially noticeable that there is an agreement on the need for flexibility in manufacturing to address both internal changes at the manufacturing echelon (e.g., a variation of process times) and external uncertainties (e.g., availability of ingredients, delivery schedules).

However, there is a lack of adoptable metrics of manufacturing flexibility that can be used to evaluate manufacturing flexibility's impact to enhance TH and reduce cost, both at the manufacturing echelon and the supply chain as a system as well as its impact on other echelons. Therefore, focusing on manufacturing flexibility as a competitive strategy induces a driving force for the success of the performance of supply chains.

The purpose of this research is to present an applicable methodology for the evaluation of flexibility in a supply chain called *Flexible Discrete Supply Chain (FDSC)*. The FDSC structure consists of a supplier, manufacturer, distributor, and customer as its conceptual model.

Two main performance indicators – TH and cost are used to study the FDSC performance. This study utilizes four dimensions: volume, delivery, mix, and innovation (VDMI) flexibility. Quality function deployment is used to translate the dimensions of

flexibility to key metrics that can be controlled in a discrete-event simulation (DES) model. The DES model is used to generate data, and for configuring VDMI metrics. The data is used for further sensitivity analysis.

The developed methodology is verified and validated using data from a real case study. It is applicable to all supply chains within the FDSC criteria.

This study contributes to the body of knowledge of supply chain flexibility through technical, methodical, and managerial implications. It clearly illustrated scenarios and provided guidelines for operations managers, to test among VMDI flexibility to maximize TH constrained by cost. Key directions for future research are identified.

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1 Introduction

1.1 Background

Supply Chain Management as a special topic entered the arena of operations management in the early 1980s (Blanchard, 2010; Feller et al., 2006) and has continued to gain popularity as an operations strategy to improve organizational competitiveness (Gunasekaran et al., 2008). Any supply chain system's primary goal is to ensure a reliable supply and demand so that products are available based on customers' expectations. This primary goal is not consistently achieved as supply chains inability to meet service level, quality, and cost desired by customers. More specifically, supply chains are under pressure to meet these performance expectations under conditions in which the supply chain's access to global network of suppliers and customers is fluid to competition and uncertainties. The globally competitive market significantly increases the challenges for uncertainties in demand with adverse effect on supply chain performance.

Key categories of supply chain performance are metrics related delivery and cost. Examples of delivery-based metrics include on-time delivery and backlog orders, to name a few. Instances of cost-based metrics can include inventory costs, cost expedition, and overtime. One fundamental concept in understanding supply chain

performance is Throughput (TH) as presented by Little's Law (Hopp and Spearman, 2011):

$$TH = \frac{WIP}{CT} \quad (1.1)$$

Work-in-Process (WIP) is the amount of inventory in the system before the product reaches the customer. Cycle Time (CT) is the period between initiating an order and completion of the order for customers. TH is a key metric that impacts delivery and cost metrics and captures the number of units supplied to the customer in a specified period.

Two strategies are implied in enhancing a supply chain's performance. The first strategy is to focus on WIP, providing additional resources within the supply chain to enhance TH. The second strategy is the reduction of CT. Reducing CT is highly related to operational excellence principles such as Lean, Six Sigma, and Theory of Constraints. These specific approaches as reported by multiple studies have left a gap between desired and actual impact (Sawhney et al., 2010). Multiple reasons for this gap include the fact that flexibility and agility are not explicitly articulated in designs. Literature supports that flexibility is an important determinant of agility and there is a clear distinction between flexibility and agility (Christopher and Towill, 2001; Narasimhan et al., 2006; Swafford et al., 2008). CT can be reduced by increasing flow, reducing variation, and reducing the frequency and duration of disruptions to the system.

To enhance a supply chain's performance, the key focus has been on efficiency (to do tasks successfully and without waste). The literature has suggested agility as a means of enhancing a supply chain's performance. According to Gunasekaran et al.

(2008), agile manufacturing and supply chain management may seem to differ philosophically. They can also be complementary because of their common objective of improving organizational competitiveness. In the supply chain domain, the need for agility has grown with the recognition of creating competitive advantage through supply chains versus stand-alone businesses (Christopher, 2000; Christopher and Towill, 2001). Christopher (2000) defines *supply chain agility* as a “business-wide capability that embraces organizational structures, information systems, and logistics processes, and in particular mindsets; the ability of an organization to respond rapidly to changes in demand, both in terms of volume and variety” (p. 1).

The reason behind the agility initiative in the 1990s was to help U.S. industries become world-class manufacturing competitors in the 21st century; this initiative was coined *agile manufacturing* (Nagel and Dove, 1991). Some studies have revealed that the origin of agility as a concept came from the flexible manufacturing system (FMS) expanded to embrace a wider business context (Nagel and Dove, 1991; Christopher, 2000). Although the agility strategy is the U.S. infused, and is intended to give the manufacturing industry a competitive edge, its scope has extended such that it is neither industry-specific nor limited to manufacturing.

While supply chain performance needs to be improved, agility’s measurability requires further expansion. Arzu Akyuz and Erman Erkan (2010) affirmed that “supply chain performance measurement is still a fruitful research area” and that research is scarce especially for responsive supply chains’ performance measurements and metrics. As a gray topic in the study of agility, flexibility is recognized as an important

dimension of agility, thus implying a clear distinction between the two concepts. One of the primary characteristics of agility of supply chains or organizations is flexibility (Olhager, 2003; Prater et al., 2001; Vickery et al., 1999). Agarwal et al. (2006) also indicated the clear distinction between agility and flexibility by suggesting how the “physical components” (echelons) may be configured to be flexible, and then determine supply chain agility. Moreover, Olhager et al. (2002) underlined the importance of setting up one or more of the supply chain echelons to be fast or flexible may increase supply chain agility. Therefore, in this study agility includes flexibility. However, nowhere in the literature has flexibility, with well-accepted measuring dimensions been integrated into supply chain performance.

Moreover, measures of flexibility on a specific machine or plant level exist and are thoroughly studied (Beamon, 1999; Sethi and Sethi, 1990) that paved the way for identifying the gaps associated with flexibility studies. Key points are enumerated below leading to further discussion in the gap in literature in the subsequent subsection.

- 1) Complex systems such an entire supply chain has not been extensively studied.
- 2) The role of flexibility in supply chain performance has not been thoroughly evaluated.
- 3) The importance of agility has not been assessed from flexibility perspective.
- 4) There is a lack of sensitivity analysis to check the dimensions of agility by focusing on flexibility in discrete-event simulation. Figure 1.1 presents this study’s conceptual framework for integrating agility into the design of supply chain performance, using dimensions of flexibility. The figure shows flexibility as the centerpiece of this study.

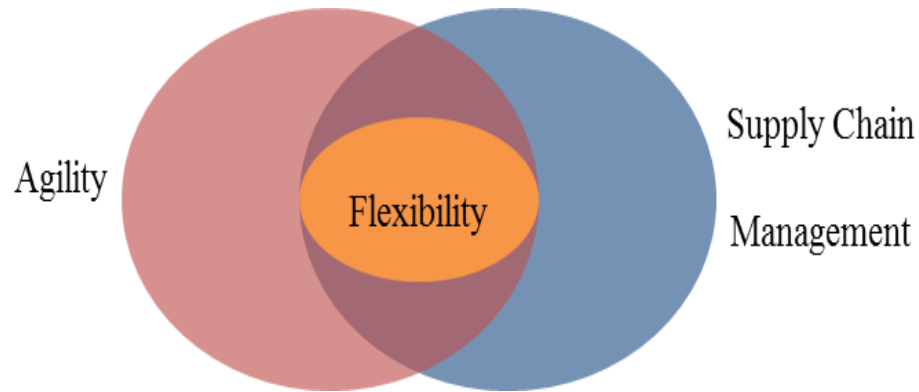


Figure 1.1: Relationship of flexibility and agility

1.1.1 Gap in Literature

The literature related to supply chain agility was presented using a systematic and comprehensive literature review. It started with simple definitions, relationships of concepts or strategies, modeling, trends and controversies, and concluded with identification of the research gap. This section provides a summary of the key supporting literature that highlights the research gap. A more detailed literature search is provided in chapter 2.

Arzu Akyuz and Erman Erkan (2010) indicated in their literature review on supply chain performance that there is a need for “framework development, empirical cross-industry research, and adoption of performance measurement systems for the requirements of the new era” of supply chain management such as in agility. “The manufacturer is a crucial part of supply chain and hence the flexibility of the manufacturer has a major bearing on the overall supply chain agility” (Kumar and Deshmukh, 2006). This implies the importance of the role of the manufacturing supply

chain performance. The performance of the supply chain can be enhanced using agility strategies. The authors also asserted that even though flexible manufacturing systems and its associated technology has progressed significantly while still there is opportunity for improvement.

While literature supports that flexibility is an important determinant of agility (Christopher and Towill, 2001; Narasimhan et al., 2006), *the dimensions used in flexibility are often not comprehensive and no consensus exists*. For example, Upton (1994) provides 14 dimensions of flexibility, while others either categorize these into few groups, as internal capabilities and competencies (Naim et al., 2006) or literature focus only on a subset of the 14 dimensions (Kumar and Deshmukh, 2006).

Even though the fundamental ideas lay on consensus, the existence of a plethora of literature provides various perspectives on supply chain agility, which creates ambiguity (Naim et al., 2006). Agility's broad scope makes measuring and evaluating it on a fixed scale difficult leading to confusion and ambiguity (Giachetti et al., 2003). With such ambiguity in agility assessment, most measures use linguistic terms (Lin et al., 2006). Both the lack of measurability and a focus solely on manufacturing are challenges in agility being a key dimension of designing supply chains. *As such, a clear and comprehensive approach to determining supply chain agility using appropriate dimensions of flexibility does not exist. Therefore, this research focuses on understanding the role of manufacturing flexibility on supply chain performance.*

1.2 Problem Statement

To enhance supply chain performance, the concept of flexibility is introduced as part of Lean strategy. However, the literature on the dimensions of flexibility is diverse and plethora. There is lack of adaptable metrics that may be used to evaluate the impact of manufacturing flexibility on supply chain performance as a system and on other echelons. Moreover, there exists no integral approach that combines efficiency and flexibility to understand supply chain performance – effectiveness. In this study, supply chain performance is measured by TH and cost.

The key research questions are as follows:

- a) Which dimensions of the manufacturing flexibility or combinations would result in optimal TH of the supply chain?
- b) What levels of the key dimensions would result in an optimally level of TH?
- c) What is the tradeoff between optimal TH and minimum supply chain cost?

1.3 Scope and Limitation

Choosing appropriate measures to assess supply chain performance is difficult because supply chain systems are complex; the number of echelons and the number of facilities involved in each usually reflects this condition (Beamon, 1999). For the sake of simplicity as well as relevance to the case study, this research assumes a four-echelon supply chain system including supplier, manufacturer, supplier, and customers, each of which containing not more than two members.

Though the flow of information influences measuring supply chain agility are potentially important, this research focuses on the physical dimensions of flexibility to produce a variety of products in a manufacturing environment. The products are current products and new ones called innovative products based on Fisher (1997).

This study considers four dimensions of flexibility: volume, mix, delivery, and innovation (VMDI) that are explained briefly.

Volume flexibility (VF) refers to the amount or quantity of deliverables, such as raw materials from the supplier to the manufacturer or finished products from the manufacturer to distributor/warehouse and finally to the retail end.

Delivery flexibility (DF) is the range of time available or potentially possible to react to demand from the downstream supply chain members.

Mix flexibility (MF) refers to the variety of products that it is possible to accommodate within the capability of the existing system.

Innovation flexibility (IF) intends to address the need for introducing new products or the ability to modify the existing products and deliver them from one echelon to the next. This is also called new product flexibility (NPF).

This research investigates these four dimensions in three levels (high, medium, and low) each. While initial characteristics of a typical supply chain's processes mentioned above are obtained from an industry partner to define a base model, further data is generated based on a simulation model. Thus, in terms of method, this study integrates the Design of Experiments (DOE), simulation, and an optimization (via parameter tuning) to achieve maximum TH at a reasonable budget.

1.4 Approach

This study uses the following four types of flexibility—volume, delivery, mix, and innovation—with agility becoming an umbrella encompassing these dimensions. In this study, types of flexibility are also referred to as dimensions of flexibility.

A subset of literatures also shows the need to incorporate other flexibility measures such as access flexibility (that deals specifically with distribution coverage) and expansion flexibility (refers to the increase in capacity of the supply chain system as a whole). As it was stated earlier, the studied supply chain is assumed to consist of four echelons: supplier, manufacturer, distributor/warehouse, and customer-end, as shown in Table 1.1.

The table also shows the relationship between the levels of each dimension of flexibility to the corresponding supply chain structure. For instance, high volume flexibility at the supplier may suffice to compensate medium volume flexibility at the manufacturer, to provide a high level of delivery to distribution and then to the end customer. The focus is to determine the appropriate levels of flexibility at specific echelons of the supply chain to reach optimal TH (that satisfies the budget constraint) based on the four dimensions of flexibility mentioned above. This requires

- Measuring flexibility
- Allocating different levels of flexibility to different echelons of the supply chain
- Determine the appropriate levels of flexibility

Table 1.1: Relationship – dimensions of flexibility and supply chain process

Dimension of Flexibility	Level of Dimension	Supply Chain Process			
		Supplier	Manufacturer	Distributor	Customer
Volume	High	✓			
	Medium		✓		
	Low				
Delivery	High		✓	✓	✓
	Medium	✓			
	Low				
Mix	High			✓	✓
	Medium		✓		
	Low	✓			
Innovation	High		✓	✓	
	Medium	✓			✓
	Low				

As shown in Figure 1.2 three major steps are connected in a bottom-up flow. The first step indicates flexibility is driven from the dimensions that defined agility as a concept. The second step connects flexibility to the three core dimensions of CT, which enables the quantification of TH. Finally, in step 3, the generated TH is compared against expected average periodic demand to evaluate if service level met, and finally the minimum cost of optimal TH is computed. To narrow down the research scope and to test the basic assumptions, data was obtained from a local industry partner. The data includes the network of the supply chains (location and the number of strategic supply chain members at each echelon, production characteristics, market demand behavior, etc.).

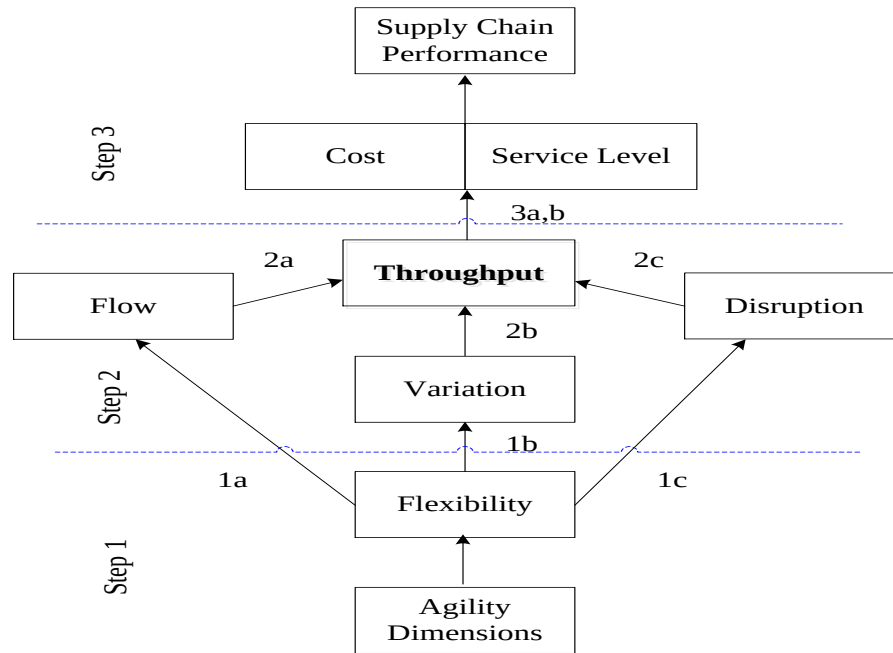


Figure 1.2: Roadmap to enhance performance

The initial discrete-event-simulation model was developed, verified, and validated for operational characteristics and performance metrics (flow, variation, disruption, etc.), as well as fulfillment strategies (push versus pull) as well as the effect of the fluidity of global suppliers on the manufacturing supply chain of a relevant industry partner. The industry collaborator focuses on cosmetics/lipstick products. The discrete-event simulation model is used to generate data, in three configurations: *no inventory* (when running innovative products); a *"partially charged"* (during unexpected disruptions); and *"fully charged"* (quick request of all inventories). The focus is on both functional and innovation products.

Next, the validated and verified simulation model was used for further investigation of supply chain performance. In the experimental settings, the four dimensions of flexibility:

volume, mix, delivery, and innovation, are assigned three levels each (high, medium, and low). The impact of each dimension, as well as the interaction among two or more of the dimensions, was analyzed, where the optimal TH is determined, constrained by total supply chain cost.

Additional iterations are carried out where the amount of TH delivered to the end customer and compares it to the expected demand. If the generated TH satisfies demand, then optimality of cost is determined. Whereas if the cost is found to be unfavorable, then the algorithm obtains the type of adjustment needed such as it examines the suitable dimension of flexibility at either high, medium or low level and where this level of flexibility dimension is applicable (that is, either at one or more of the echelons in the supply chain). These are classified based on either reducing variation or disruption or increasing flow. Similarly, if the generated TH doesn't satisfy the anticipated customer demand, then again, the loop runs to find optimal adjustments to one or more of the dimensions of flexibility at a favorable level. When making the comparison of demand versus TH, a service level corresponding to the three levels: high, medium, and low is used.

A brief synopsis of the approach is shown in Figure 1.3. Building on the framework given in figure 1.3, more details are provided in Chapter 3, where the technical details of the methodology are described. Using flexibility's four dimensions, a relationship matrix is created with process characteristics and performance metrics. The Throughput of the supply chain is determined by the flow, variation, disruption, and dimension of flexibility. Table 1.2 shows this relationship matrix.

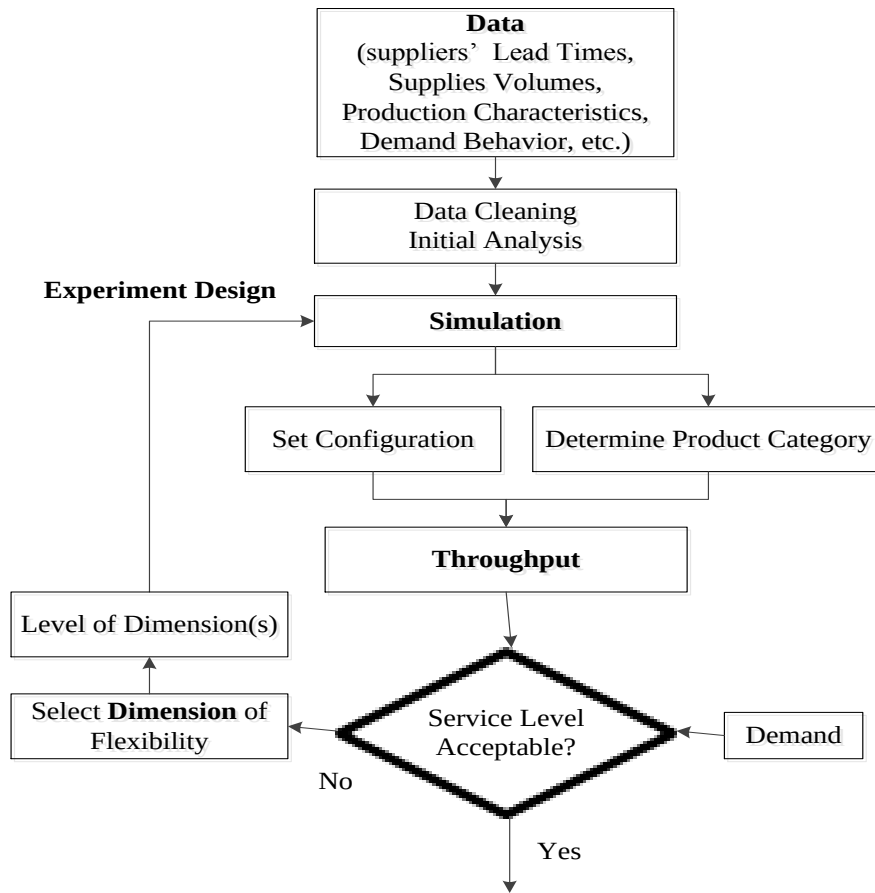


Figure 1.3: General approach

Table 1.2: Relationship matrix

	Flow	Variation	Disruption	TH
Volume	+	–	–	+
Delivery	+	–	–	+
Mix	–	+	–	+
Innovation	–	+	–	+

To further study the relationship matrix between the dimensions of CT and dimensions of flexibility indicated in Table 1.2, and the impact of dimensions of flexibility at each echelon in the supply chain shown in Table 1.1. For instance, there is positive relationship between flow and TH, meaning that TH can be increased by increasing flow. The representation of these relationships enables us to formulate the hypotheses. A hypothesis testing is discussed later in Chapter 3.

1.5 Impact

There are numbers of managerial and academic/theoretical implications of this research in terms of addressing the research gaps previously identified. This research contributes to the theoretical advancement of agility in that it ascertains the importance of flexibility as a key dimension to enhance operational performance of a supply chain. It also complements to the strategies that Lean attempts to achieve in system's operational excellence. The research also builds on Gligor and Holcomb (2012) by comprehensively focusing on the physical capabilities of agility in the supply chain. Hence, it adds to the body of knowledge through modeling to add better understanding of supply chain agility. The key contributions of the dissertation research include:

- 1) Providing supply chain managers predictive models that ascertain: the type and level of flexibility, and where it is needed in the supply chain
- 2) Illustrating a pairwise comparison of the dimensions of flexibility
- 3) Leveraging data acquisition and point of analysis problems using a simulation model instead of survey data as used in previous studies

- 4) Providing a framework to serve practitioners and researchers alike as a roadmap to determine and optimal level of supply chain agility based on product categories
- 5) Providing a definition and measures of flexibility
- 6) Designing a model that optimizes TH based on flexibility
- 7) Integrating flexibility as a design dimension for supply chain performance

1.6 Dissertation Organization

This dissertation is comprised of six chapters. Chapter 1 introduces the issues pertaining to supply chain performance. Chapter 2 describes the literature survey relevant to the concept of agility, methods, and models used to ascertain the building blocks leading to the need for developing/modeling supply chain agility. Chapter 3 discusses the detailed methodology addressing data collection, simulation, mathematical models, and experimental design. Chapter 4 validates the methodology tested using a case study in a high-volume and high-variety manufacturing supply chain. Chapter 5 presents and discusses results. Chapter 6 contains the conclusion and outlines the direction for future research.

2 Literature Search

2.1 Search Approach

An in-depth search is performed for agility and flexibility strategies. This literature search followed the systematic process proposed by both Torraco and Randolph to ensure that the goals of a successful literature search achieved. A systematic, comprehensive literature review achieves the following goals (Torraco, 2005; Randolph, 2009).

- Reports the growth or trends of an existing literature in relation to a topic or problem.
- Identifies any relations, controversies, disagreements, limitations, and gaps; formulates general statements or conceptualization.
- Evaluates or expands an existing theory, and/or develops a new theory.
- Outlines a future direction for research.

Figure 2.1 outlines the steps of the literature review conducted for agility and flexibility of supply chains.

The Web of Science database was explored by limiting the period from 1991 – 2017. The reason for setting this limit is because the concept of agility was introduced in the early 1990s. A key component of a successful literature search is to identify appropriate search terms to fit the postulated research questions.

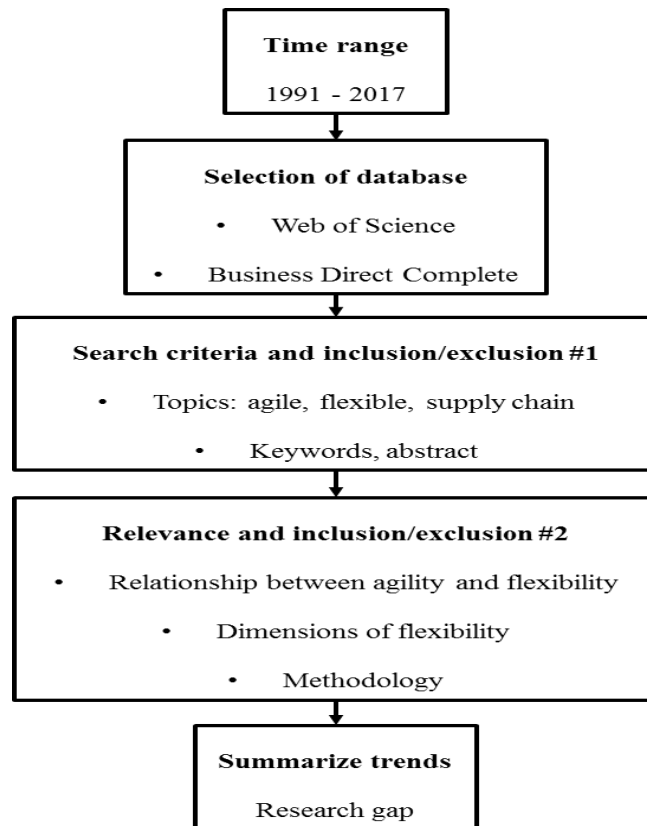


Figure 2.1: Literature review strategy

The key search words for this literature search include flexibility, supply chain, agility, volume flexibility, mix flexibility, delivery flexibility, innovation flexibility, supply chain performance, agility experiment, and measuring agility. Combination of these terms were utilized in this literature search, with a primary focus was on academic and scholarly journals that provide insight into agile and flexible supply chains. The articles utilized were from Boolean phrases composed of the keywords but limited to academic journals. Inclusion/exclusion criteria for literature includes a review of the abstract (to check relevance), scope and focus of the publication and citations. There were multiple

iterations associated with each publication during the process of formalizing of the dissertation.

A second database, Business Source Complete (through EBSCO), was also searched based on the same key words and their combinations mentioned above. Additional publications were identified and assessed based on the same inclusion/exclusion criteria. This search ensured that relevant publications were included.

EndNote was utilized to create database of publications, a permanent record of searches was created based on categorizes of dimensions of agility, domains where agility is used (e.g. manufacturing agility, supply chain agility, enterprise agility, etc.), measures of flexibility, and modeling/analysis, etc. (such as experimental design, simulation, mathematical, case study, conceptual, etc.). Obviously, there is a possibility of publications being in multiple folders.

2.2 Supply Chain Performance Strategies

2.2.1 Genesis of Agility

The genesis of agility as a concept is driven from the flexible manufacturing system (FMS). Agility is expanded to embrace a wider business context beyond a manufacturing function (Nagel and Dove, 1991; Christopher, 2000). The definition of agility is context specific, which means due to its multidimensionality and multifaceted usage, there is no standard accepted definition. A review of literature shows that lack

of a standard definition for agility creating ambiguity that hinders further study (Giachette et al., 2003; Li et al., 2009; Gligor and Holcomb, 2012; Alberts, 2015).

An example of definition of agility is presented by Christopher (2000). He defines supply chain agility as a “business-wide capability that embraces organizational structures, information systems, and logistics processes, and in particular mindsets; the ability of an organization to respond rapidly to changes in demand, both in terms of volume and variety.” Another definition of agility is that it characterizes “a system’s ability to change rapidly” (Fricke and Schulz, 2005).

The definition may be ambiguous, but the benefits of agility have been well documented. Examples of such advocacy of agility are presented below.

- To increase “competitiveness and mastery of uncertainty and variability” (Goldman et al. 1995), for survival and prosperity in a competitive environment that is continuously changing and faces uncertainties (Gunasekaran and Yusuf, 2002; Alberts, 2011).
- To cope with global competition (Kasarda and Rondinell, 1998).
- To enrich the customer and to create cooperative production relationships (Gunasekaran, 1998); “satisfy customer orders, introduce new products frequently in a timely manner”, and possess ability to “get in and out of its strategic alliance speedily” (Gehani, 1995).
- To cope with an ever-changing market requirement for superior quality goods consistently (Goldman, 1995; Kidd, 1995; Booth, 1995; Gunasekaran and Yusuf, 2002).

- To maximize customer service levels while the cost of goods is minimized (Gligor and Holcomb, 2012).
- To enhance information based and value-added products/services (Goldman and Nagel, 1993; Goldman, 1995).
- To gain the capability of responding to issues of social and environmental nature (Goldman and Nagel, 1993; Goldman, 1995; Kidd, 1995; Vazquez-Bustelo et al. 2007).
- To respond to customer requirements measured based on price, quality, quantity, delivery time, etc. among others (Katayama and Benett, 1999).
- To reduce cost (Katayama and Benett, 1999).

Even though agility as a concept or paradigm seems to attract a wide range of interest in the multidisciplinary domain, regardless of industry sectors, there is a vigorous misconception in the literature with other terminologies and/or supply chain strategies, such as resilience, lean, and flexibility. A brief description indicating the key distinguishing characteristics are provided.

2.2.2 Agility and Flexibility

In this study, the following brief distinctions between agility and flexibility are adopted to avoid confusion between these two important strategies. In the supply chain context, supply chain flexibility and supply chain agility are distinct strategies, in a way that the higher the levels of supply chain flexibility, the higher will supply chain agility. (Swafford et al., 2008). Swafford et al. (2008) further elaborate this relationship as “flexibility is an

antecedent of agility”. In a similar note, other authors support flexibility as a determinant of agility. For example, according to Kidd (2000), as agility embraces nimbleness, quickness, and dexterity, flexibility focuses on adaptability and versatility. Goldman et al. (1995) summarizes the distinction between the strategies or concepts as follows: “agility is a measure of the reaction time to change while flexibility is a measure of the reaction capabilities for change; agility is typically associated with overall organizational abilities”. Others limit flexibility only to those operational abilities, for typical operations such as in manufacturing (Gupta and Somers, 1992; D'Souza and Williams, 2000).

Based on the previous works discussed it can be concluded that flexibility is a key part of agility. That is, *agility is the umbrella concept, which encompasses flexibility as its determinant characteristic or element.*

2.2.3 Agility and Resilience

Although there are different views, one aspect of exploring the relationship between agility and resilience is indicated by Christopher and Peck (2004) as follows. Agility along with flexibility are used as attributes to define resilience. This means, resilience involves agility in a way to help a system to organize for responding to a change quickly. Dalziel and McManus (2004) posited an implication of higher agility to higher resilience, while Morello (2002), on the contrary, and suggest that agility may lead to lower resilience by introducing new risks and vulnerabilities.

However, there are conflicting viewpoints whether agility enhances or deteriorates resilience. *For supply chain, agility can be considered as characteristic of resilience. While agility can be used to respond to uncertainties such as dynamic demand from the customer's end of the supply chain system and to enhance performance, additional characteristics will be needed to get back to the original well-being of the supply chain system whenever such uncertainties cause unanticipated disruptions.*

2.2.4 Agility and Lean

There exists a divergent view, one that sees lean and agile in isolation and progression suggesting that lean is a prerequisite leading to a natural development of agile systems (Booth, 1995 and 1996; Ward, 1994). The second view focuses on their interconnection and the possibilities of adopting them at the same time in different business environments/circumstances (Naylor et al., 1999; Christopher, 2000). According to Sarkis (2001), agile manufacturing is a combination of FMS and lean manufacturing principles.

The conceptual distinction between Lean and Agile systems was first demonstrated in the work of Christopher (2000). The author used three main evaluation factors: variety, predictability, and volume; where high variety along with high unpredictability (demand volatility) requires agility while lean works best in the environment featured in high volume, low variety and ease of predictability in demand.

Some literature also suggested a hybrid approach that combines lean and agile. This hybrid approach is called “Leagile” (Naylor et al., 1999; Van Hoek, 2000; Mason-Jones et al., 2000) and it is meant to be applicable to different conditions of demand responsiveness. Again, there are conflicting viewpoints in the literature. For example, Mason-Jones et al. (2000) suggested that agility can be used in downstream while lean fits upstream from the decoupling point of the supply chain. The goal of the Leagile concept and the classification of where agility and lean fits in regard to the decoupling point, is to create cost effectiveness of the upstream chain (using lean) and high service levels in a volatile marketplace in the downstream chain (using agility).

On the other hand, Van Hoek (2000) argues on the effectiveness of the Leagile approach to supply chain performance in an operational sense but falls short of providing support for fundamentally challenging the concept of agility. That is, Leagile must fit with an agile approach instead of pure lean with respect to supply chain performance to be applied properly (van Hoek, 2000). Describing it in simple terms, Booth and Harmer (1995) distinguished lean from agile as follows: lean is for “enhancement of mass production” and agility is for “breaking out of mass production” into mass customization.

In addition, to providing distinguishing features between lean and agile, the above discussion also indicates research gaps. *There is an opportunity for exploring the advantages of complementing lean principles with agility to enhance supply chain performance.*

2.3 Measures of Agility

The concept of agility has been moving towards acceptance in terms of its importance to enhancing supply chain performance. However, there is a gap in literature regarding the understanding key dimensions or determinants for supply chain performance.

Harrison et al. (1999) suggested four dimensions: market sensitivity, virtual organization, network based, and process aligned. Gligor and Holcomb (2012) expanded the dimensions into five: alertness, accessibility, decisiveness, swiftness, and flexibility; the first three are information related while the remaining two dimensions address capabilities.

Goldman et al. (1995) indicated that agile manufacturing has the following dimensions (a.k.a. characteristics or factors): 1) enriching the customer, 2) cooperating internally and externally, 3) leveraging the impact of people and technology, and 4) adaptability. This is an extension of an earlier study by Goldman and Nagel (1993), which refers to being agile in a broad sense as context specific or possession of extraordinary capabilities (Iacocca Institute, 1991). These may be categorized for simplicity as enriching the customer, cooperation (integration and collaboration), knowledge management or information sharing, and adaptability.

To differentiate from lean manufacturing, Booth (1995), emphasized two dimensions: flexibility and responsiveness. Kidd (1994) and D'Aveni (1994) refer only to integration and responsiveness ("speed and surprise") respectively, in their effort to define characteristics of agility. Cho et al. (1996) underlined responsiveness and mass

customization (providing customized products for customer demand) as a means for survival to uncertainties.

Fliedner and Vokurka (1997) indicate mass customization and flexibility (especially the volume flexibility and mix flexibility) as key enablers. Other studies focus mainly on responsiveness (for example see Yusuf et al., 2004; Almahamid et al., 2010; Vickery et al., 2010; Zhang, 2011).

The development of supply chain agility from a manufacturing perspective is presented below. Christopher (2000), van Hoek et al. (2001), Lee (2004), and Jain et al. (2008) concentrated on responsiveness, either referring to speed and/or effectiveness of responding to customer expectation with volume and variety.

As research expanded so did the agility dimensions with flexibility emerging as a key dimension of agility. Lee (2002) and Sehgal (2010) aimed at the strategic importance of responsiveness and flexibility. Costantino et al. (2012) focused on flexibility obtained in terms of integration of different organizations (supply chain members). Holweg (2005) used three dimensions of responsiveness, namely product, process, and volume. These can be viewed as “system flexibility”. *There still exists the need to comprehensively explore the role of flexibility on the agility of a supply chain.*

Others added different agility dimensions. Li et al. (2008) and Conboy and Fitzgerald (2004) see the importance of alertness. Sharif et al. (2006) embrace for a need of total supply chain integration or alignment.

2.4 Modeling Agility - Methods

This section reviews the relevant literature related to modeling supply chain agility. Modeling includes conceptual development, modeling, analysis and software utilization and development to gain insight into the role of agility in supply chain performance. The modeling approaches to assess supply chain performance can be delineated into four categories (Beamon, 1998). These four categories are deterministic analytical models, stochastic analytical models, economic models, and simulation models. Deterministic analytical models are utilized when variables of interest are known and can be specified. Stochastic analytical models are utilized when one or more of the variables of interest are not known, so probability distributions are utilized to approximate values. Economic models relate supply chain agility in economic terms. Simulation models provide the ability for experimenting with supply chain parameters.

Min and Zhou (2002) have taken information technology into account and created a taxonomy of supply chain modeling as deterministic, stochastic, hybrid (a combination of deterministic and stochastic) and information technology driven.

Another modeling classification is based on four different type of decisions: location decisions, production decisions, inventory decisions, and transportation decisions (Ganeshan and Harrison, 1995). They further classified the modeling into three major categories, which are briefly described as follows.

- 1) Network design – models used for strategic level decisions such as establishment of networks and their associated network of flows,

- 2) “Rough cut” – models that provide guidelines for operational level decisions by taking a supply chain echelon and analyzing its impact on other echelons in the network, and
- 3) Simulation.

Some of the most cited works in modeling agility are presented in Table 2.1. Along with the variety of dimensions described in section 2.3, the modeling techniques and tools varies as well. Gunasekaran et al. (2008) focused only on speed, flexibility, cost, and quality, whereas other literature shows about 15 or more variables in modeling supply chain agility (for example, see Agarwal et al., 2007).

2.5 Dimensions of Flexibility

The literature review identifies flexibility is a determinant dimension of agility in the supply chain. In addition, according to Christopher (2000) flexibility is key for an agile organization. Therefore, measuring flexibility is an indicator of the level and amount of agility required for measuring supply chain performance. Table 2.1 shows examples of techniques used in modeling agility.

White et al. (2010) identifies four critical practices required for just in time (JIT) manufacturing systems. These are in order of importance quality, reliability of delivery, volume flexibility, and low-cost practices. This emphasizes the importance of flexibility to the performance of a manufacturing system. Oberoi et al. (2007) through their literature survey developed a hierarchical taxonomy of manufacturing flexibilities, classified into three hierarchical levels. These are strategic, tactical, and operational flexibility.

Table 2.1: Agility modeling techniques

Author (Year)	Purpose	Data/Information Acquisition	Method(s)	Implications for practice, research, theory
Naylor et al. (1999)	Case study	Interviews and secondary data	Literature Review – Benchmarking	Leagility
Christopher (2000)	Conceptual Framework	Literature Review		Leanness vs. Agility, Leagility, roadmap to agility
Prater et al. (2001)	Conceptual Framework	Interviews, case study audit	Literature Review – Benchmarking	International/external vulnerability vs. supply chain responsiveness
Van Hoek et al. (2001)	Conceptual Framework	Survey, interviews		Agility framework to develop audit of capabilities
Bruce et al. (2004)	Case study	Interviews and secondary data	Exploratory qualitative	
Agarwal et al. (2006)	Framework, Case study	Interviews	Analytic Network Process	Lean, agile, and leagile: market winning, market qualifying
Lin et al. (2006)	Agility evaluation model	Survey, interviews	Fuzzy Logic	Assessment tool, major factors/obstacles to enhance agility
Agarwal et al. (2007)	Case study	Brainstorming, interviews	Interpretive structural modeling	Interrelationship among variables
Gunasekaran et al. (2008)	Conceptual Framework		Literature Review	Responsive supply chain (RSC)
Swafford et al. (2008)	Conceptual Framework	Survey	Structural equation modeling	Domino effect of information technology, supply chain flexibility & agility, and overall supply chain performance

Examples for each of these taxonomies is given below, following the description of methods in Table 2.1.

- a) Strategic flexibilities at an organizational level (e.g., new product flexibility, and market/delivery flexibility),
- b) Tactical flexibilities at a plant level (e.g., mix flexibility, volume flexibility, and modification flexibility), and
- c) Operational flexibilities at the shop level (e.g., equipment flexibility, material handling flexibility, routing flexibility, material flexibility, and program flexibility).

Oke (2005) identified five sources or drivers of volume flexibility: demand variation (i.e., variability in actual demand levels), demand unpredictability, customer influence in determination of lead time, short product lifecycle, and short product shelf-life. Moreover, the author suggests that models for supply chain flexibility should distinguish between those internal to the supply chain, called *internal flexibilities* and those viewed externally by customers, which are called *external flexibilities*.

Within this context of categorizing the dimensions of flexibility into either internal or external, Naim et al. (2006) provided dimensions pertaining to the two major parts: external flexibility includes factors such as a new product, mix, volume, delivery, and access flexibility. Internal flexibility, according to the author typically refers to transportation-related factors such as fleet, vehicle, node, etc. The authors' focus was specifically on transport flexibility.

Parker and Wirth (1999) and Das (1996) describe volume flexibility as a range limited by break-even point of output capacity and profitable range of product output,

respectively. Beamon and Chen (2001) provided an approach by defining each (volume, mix, delivery, and new product) flexibility as a function of time. Mathematical models addressing the issue of mix flexibility can be found in the works of Chryssolouris and Lee (1992), Bateman et al. (1999), Beamon and Chen (2001), and Goyal and Netessine (2011).

Gligor and Holcomb (2012) in their comprehensive literature review on supply chain agility mentioned that most of the literature has been explored centering on manufacturing flexibility, lean manufacturing, or supply chain speed. On the other hand, although the scope of this study is centered on manufacturing supply chain, the work of Gosling et al. (2010) is mentioned here to show the veracity of measuring flexibility.

Gosling et al. (2010) have rationalized two antecedents (vendor flexibility and supplier flexibility) as internal capabilities of supply chain flexibility through case studies in the construction industry and examined five dimensions of flexibility: new product flexibility, mix flexibility, volume flexibility, delivery flexibility, and access flexibility. The first four dimensions are the focus in this dissertation. A summary of the dimensions of flexibility is tabulated and presented at the end of the next section for convenience. However, it is evident that no study to date comprehensively examines the dimensions of flexibility to determine, as well as predict, the agility in the supply chain. *This literature search reaffirms the research intent presented in chapter 1.*

2.6 Industry Perspective and Summary

Fisher (1997) suggested that a supply chain design should match the product type (innovative products or functional products). If the demand of the product is unpredictable or it exhibits short lifecycle, mix flexibility may be the right means for responding to the issues of unpredictability and the short product life cycles. For example, for a supply chain involving a process or continuous manufacturing such as cement production, volume flexibility can be the right match to create a responsive supply chain. If a manufacturing or fulfillment strategy is make-to-order (example: plastics manufacturing; textile, clothing, and footwear industry), it is usually having low-volume, high-variety product characteristics (for example, see Baramichai et al., 2007; Perry and Sohal, 2001).

Christopher and Towill (2001) proposed a manufacturer/logistics integration model in which three levels of implementation are identified: principles of postponement and quick fulfillment, programs to support the principles, and actions to aid the programs (example: setup time reduction, information enrichment, etc.). Since the automotive industry supply chain exhibits both leanness and agility, Azevedo et al. (2012), introduced “Agilean index” for assessing the lean and agile behavior. However, the authors did not provide any of the dimensions of flexibility.

Booth and Harmer (1995), as one of the early studies on agile manufacturing, envision agile manufacturing as a best practice. The authors focused on applying agility in a ceramic manufacturing environment with a lead time of 12 to 16 weeks.

With a concentration on supply chain performance of the textile and clothing industry using case studies, Bruce et al. (2004) identified how to leverage lean, agile, and leagile strategies to address the business characteristics of this industry sector. A similar application can also be found in the study by Mason-Jones et al. (2000). The case studies cover specific sectors within the textile and clothing manufacturing supply chain, such as manufacturers of high street fashion, fiber producer, sportswear accessory design, and premium brand manufacturers and retailers.

Some of the dimensions of flexibility in terms of external flexibility in the textile and clothing industry may include “short product lifecycle, high volatility, low predictability, and a high level of impulse purchasing” (Bruce et al., 2004). Christopher et al. (2004) attributed these natures of the market, which the fashion products possess as favorable for application of agility to enhance supply chain performance. This means, it reinforces the fact that textile and apparel industry is partly driven by the demands of the fashion business. The authors further argued that to cope with the turbulent challenges of the fashion market, “conventional organizational structures and forecast-driven supply chains” are not enough. This argument leads to the need for an agile supply chain of the organization.

The fashion industry is a typical example of high mix and low volume demand. Purvis et al. (2014) presented a case study in a clothing sector (a UK based fashion sector) and illustrates the importance of volume flexibility and mix flexibility to strategize either lean, agile, or leagile paradigms, as well as where exactly the flexibility should be introduced (vendor flexibility versus sourcing flexibility).

Salvador et al. (2007) presented an in-depth case study analysis on the impact of volume and mix flexibility and the tradeoff that exist between these two dimensions of flexibility, on the implementation of a build-to-order system for lawn and garden equipment manufacturing supply chain. The authors' suggestion for managers and practitioners is to prioritize volume or mix flexibility, alter specific requirements in processing, and/or to introduce a suitable technology or operation.

Through their survey-based data collection, Zhang et al. (2003) explored volume and mix flexibility in a wide range of industries such as “fabricated metal products”, “industrial and commercial machinery”, “electronics and electrical equipment and components”, “transportation equipment”, and “instruments and measurements equipment”. Baker (2008) through a survey of six European companies specializing in the distribution of products, five in the fast-moving consumer goods (FMCG) sector and one in publishing, identified that even within the same sector the dimensions of flexibility used varies. For example, according to Baker (2008) in the cosmetics/beauty industry, agility may be used to address volume, delivery, and mix flexibility; whereas in supply chains such as Global Drinks Ltd., the authors found volume flexibility as a primary dimension to tackle market growth and seasonality.

Therefore, *it is reasonable to conclude that there is no work to date that focuses on a comprehensive investigation of supply chain performance using the dimensions of flexibility.* In addition, only volume and mix flexibility are the two commonly applied dimensions. Nevertheless, they may provide conflicting results requiring tradeoffs to enhance supply chain performance. Table 2.2 provides a summary of the applicability of

volume and mix flexibility in various manufacturing industry sectors. As discussed in the previous section, a summary of the dimensions of flexibility is presented here for convenience. Table 2.3 illustrates the dimensions of flexibility with brief description of each, and selected sources. Besides to summarizing the dimensions of flexibility, it is essential to reiterate the key theoretical foundations leading to focus on manufacturing flexibility before moving on to Chapter 3.

As discussed above, a clear distinction between flexibility and agility was underlined supporting by existing literature. Although information flow and physical dimensions of measuring supply chain agility are potentially important (Gligor and Holcomb, 2012), the focus of this research is on the physical dimension.

Table 2.2: Summary of applications

Industry/Sector	Volume		Mix		Author (Year)
	High	Low	High	Low	
Manufacturing/ Job-shop or make-to-order		✓	✓		Sadowski (2010)
Toys and Furniture		✓	✓		Sadowski (2010)
Manufacturing/ Continuous process	✓			✓	Sadowski (2010)
Plastics, footwear, apparel (if make-to-order)		✓	✓		Baramichai et al. (2007); Bruce et al. (2004); Perry and Sohal (2001)
Cosmetics/lipstick, street-fashion clothing (fashion)		✓	✓		Christopher et al. (2004); Bruce et al. (2004); Purvis et al. (2014); Baker (2008)
Ceramics	✓		✓		Booth and Harmer (1995)
Lawn and garden equipment		✓		✓	Salvador et al. (2007)

Table 2.3: Major dimensions of flexibility

<i>Dimension of Flexibility</i>	<i>Description</i>	<i>Author (year)</i>
<i>Volume flexibility</i>	The ability to change the output level of products to address variable demand.	Carlsson (1989), Slack (1987, and 1991), Sethi and Sethi (1990), Hyun and Ahn (1992), Suarez et al. (1996), New (1996), D'Souza and Williams (2000)
<i>Delivery flexibility</i>	The ability to change delivery dates. Suitable if delivery dates change regularly and costs are associated with unmet delivery dates.	Sethi and Sethi (1990), Beamon (1999), Zhang et al. (2003)
<i>Mix flexibility</i>	The ability to change the variety of products produced. Suitable for stationary demand for multiple product types.	Boyer and Leong (1996), Sethi and Sethi (1990), Gupta and Somers (1992)
<i>New product flexibility</i>	The ability to introduce and produce new products (including existing products); for products with short life cycles.	Sethi and Sethi (1990), Slack (1991), Beamon (1999), Lee (2004)
<i>Access flexibility</i>	The ability to provide extensive distribution coverage.	Lee (2004), Naim et al. (2006)
<i>Expansion flexibility</i>	The ability to add capacity to a system.	Parker and Wirth (1999), Upton (1994)

That is, flexibility as a physical dimension of agility is used visa-vise the possibility of generating simulation driven data, illustrated later in Chapter 3 and subsequent chapters.

The material flow is broadly classified as innovative products and functional products (Fisher, 1997). In this study, the products are categorized as steady-state and

transition products. A broader description of these products and the corresponding scenarios and supply chains they represent is given in Chapter 3.

3 Research Methodology

3.1 Motivation and Conceptual Framework

This chapter highlights the research methodology that integrates flexibility as a valid strategy to enhance supply chain TH at a minimum cost. The cost in this case is the supply chain cost, which includes average holding cost of raw materials per period (inventory cost), average operating costs of processes in the manufacturing echelon (production cost per unit), transportation cost to/from the manufacturing, and inventory costs at the manufacturing and distribution echelons. At the customer echelon, costs related to obsolete products and late delivery of products (backorders) are also important to include. However, the percentage of costs arising from obsolescence and backorders is assumed to be negligible as compared to the total supply chain cost (e.g. see Kahn, 2014). Noting this assumption will serve to ease the difficulty of modeling complex supply chain structures during experimentation, simulation, and optimization steps. A brief highlight of these steps and other sections of this chapter is given below, which will be followed by with details in separate sections.

First, the conceptual framework for the methodology is presented. Second, the class and supply chain setup considered to implement the methodology is described. Third, the performance system is described. Fourth, the experimentation is presented via design of experiments (DOE). Fifth, simulation modeling for the purposes of testing

the designed experiments is introduced. Next, statistical analyses of the simulation runs are discussed. Then, the optimization of the flexibility strategy is described, followed by a summary of the chapter.

3.1.1 Motivation

To enhance TH, two implicit strategies can be used, which emanate from understanding the basics of Little's law (see equation 1.1). The first strategy deals with modifying the levels of work-in-process (WIP) represented by additional resources in the supply chain system. The second alternative strategy focuses on reducing cycle time (CT). However, two problems exist with the perspective of these strategies. The first problem is that most of the efforts on reducing CT focused on operational excellence principles, using approaches such as Six Sigma, Lean, and Theory of Constraints. As reported in multiple studies (e.g. Sawhney et al., 2010; Nave, 2002), these approaches leave a gap between desired and actual impact. This study bridges that gap by explicitly integrating flexibility into the DNA of manufacturing system design. The second problem is in shifting the focus from efficiency to effectiveness. *This research defines effectiveness as a function of efficiency and flexibility. In this particular case, effectiveness is to be measured using TH. TH is an important measure of effectiveness since it refers to the number of units produced per unit time (e.g. by the manufacturing echelon) as indicated in equation 1.1, and the output is compared with what is desired by the next echelon and/or at the system level. Hence, TH_mfg (throughput of manufacturing) and TH_sys (throughput of the supply chain) refers to the effectiveness of the manufacturing and*

effectiveness of the supply chain system, respectively. Therefore, flexibility in a manufacturing can result in effectiveness in a supply chain. Since there is a level of confusion as to how supply chain effectiveness is measured and enhanced, efficiency is briefly described first followed by effectiveness.

Efficiency measures the amount of inputs needed or that can be utilized to maximize the number of products, while at the same time it results in a minimum operational cost. Efficiency is a productivity measure that focuses merely to utilize fewer input resources, including cost of running these resources, to maximize output products. From supply chain point of view, an efficient supply chain may be created for one of the echelons alone, say the manufacturing echelon, by ignoring the negative impact such an efficient echelon might cause to the other echelons such as those pre and post the manufacturing echelon, or at the entire supply chain system level.

On the other hand, effectiveness measures the amount of output products per time unit achieved with what is desired by the supply chain partner in the downstream echelon and/or what would be expected from the upstream echelon. This means, effectiveness encompasses the impact of the efficiency met at one echelon, say manufacturing, to other echelons by looking beyond the basic inputs resources. Therefore, effectiveness is defined here as a function of efficiency, manufacturing flexibility, and cost. Now, the cost is not limited to manufacturing cost but also other costs (see section 3.8.1 for details). *This research systematically links flexibility to TH and subsequently to cost to evaluate the efficiency and effectiveness of supply chain.*

The objective is to determine the flexibility parameters and their levels that enhance supply chain TH, within total supply chain cost constraints. Specifically, this will determine the effects of the levels of volume, mix, delivery, and innovation flexibility.

Based on the motivation and objectives above, the *research hypothesis* is explained below. Null hypothesis (H_0): There is no statistically significant effect of the selected dimensions of flexibility (volume, mix, delivery, and innovation) at any level (low, medium, or high), when applied at a manufacturing echelon, on TH and cost of manufacturing and the supply chain system. The following hypothesis is formulated to further elaborate the research hypothesis above. Hypothesis: an increase/decrease in each dimension of flexibility at the manufacturing echelon has a significant positive/negative impact on operational performance (TH or cost) of the conceptual supply chain.

Furthermore, this effort provides a predictive model to determine the amount and level of flexibility required as a form of statistical analysis. This will be built on further in section 3.7. Within the above discussions in context, the study is presented in two major scenarios: Steady-state and Transition. *Supply Chains under Transition are in the process of adjusting to a change in product mix or product characteristics, the latter is usually driven by innovation (introduction of new products). Steady-state supply chains operate in non-Transition periods, where the customer is likely to drive demand variability.* This is a one characteristic that distinguishes the supply chain selected to develop the model.

3.1.2 Overview of Conceptual Framework

The overview of the conceptual framework comprises of two major themes are presented – operational definitions and a brief description of the research roadmap. The operational definitions of key terminologies are provided below.

High volume: the number of products of a given product type, that can be delivered, corresponding to high volatile demand volume. In this case, this refers to up to 1200 stock keeping units (SKU) are produced in each product type.

High product mix: the variety of products available to deliver in each stock keeping units' category. In this case, the product mix includes a minimum of nine product families in 36 SKUs alone.

Introduction of new products: product innovation used to enhance the product mix by introducing new products.

Discrete manufacturing: a batch production system that moves products from one stage to another. In this case, the system is machine-driven, requiring setups to accommodate high product mix. In other words, there is minimal human intervention in the production system.

The roadmap of the 6 phase research methodology is presented in Figure 3.1, followed by detailed discussion pertaining to each of these phases. The performance system design consists of two main components:

- a) defining measures for supply chain performance, and
- b) defining supply chain flexibility. TH (CT and WIP) defining measures for supply chain performance are impacted by flow, disruption, and variation.

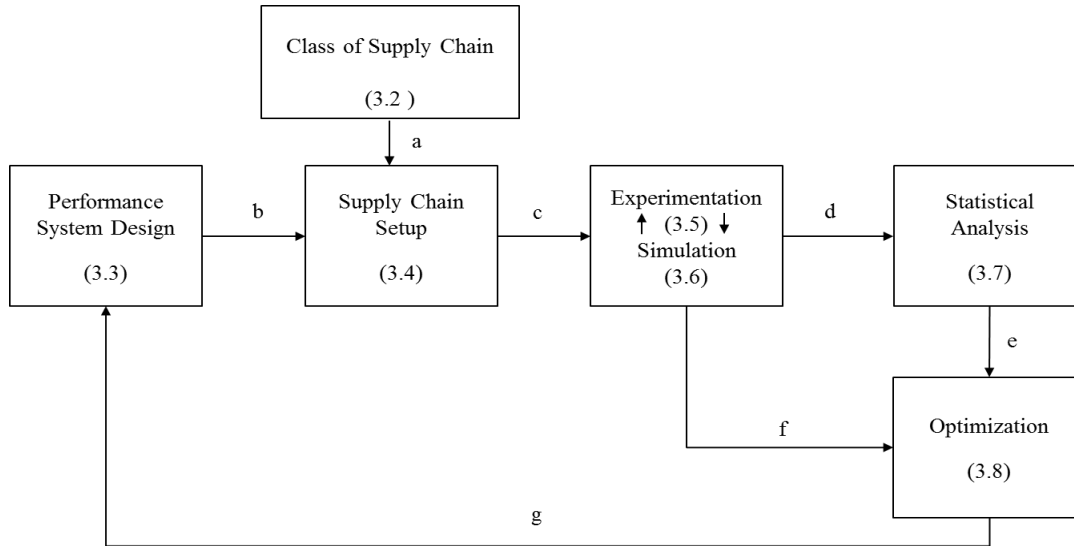


Figure 3.1: Roadmap of Methodology

Sawhney et al. (2019) used flow, disruption, and variation as leading indicators and TH and cost as lagging indicator(s). **Flow** in this case refers to how the entities of the system (e.g. ingredients, work-in-processes, finished products) are routed from one step to the next step along with the system, such as how these entities move from supplier to manufacturer, within the manufacturing processes, and to the distributor, etc. Flow indicates whether the movement is in single units, in batches or lots, etc. **Variation** refers to anything that causes the manufacturing echelon or the supply chain as a system to deviate from its predefined characteristics or operational behaviors. For example, if there is an increase in customer orders from the average order (say an average is computed from historical data of demand), this reflects a variation coming from the customer end of the supply chain. Within the manufacturing echelon, an increase or decrease in the setup time needed between consecutive lots or different

products is another indicator of variation. **Disruption** refers to anything caused by internal factors or plans (e.g. setup time, maintenance, etc.) that interrupts the flow of entities or it leads to exacerbate the variability to the existing or predefined operational characteristics.

The second component introduces the four dimensions of flexibility: volume, mix, delivery, and innovation (VMDI). CT's dimensions (flow, disruption, and variation) are manipulated to compute the level (high, medium, and low) of each dimension of flexibility, at the supply chain setup. High, medium, and low levels represent three configurations, namely no inventory, partially charged, and fully charged, respectively. The ratio of expected TH under low level to medium and high levels is set to match the three configurations.

The design of experiments is created with an input from the supply chain setup. The purpose is to generate data in the next step – simulation, to study the effect of the dimensions on TH and cost at each echelon. A discrete event simulation model is used to generate data related to the following performance indicators. Every time an experimental setting runs, a database of operational metrics (e.g. TH, WIP, and CT) are collected. The simulation software provides options to include costs associated to a “resource” (e.g. equipment or worker) or “location” (e.g. process) usage per time period and enables to study an average total cost per given TH and CT. At the end of the simulation run, an average total cost is one of the metrics collected.

The analysis step takes input from the database of operational metrics (e.g. setup time, process variation, etc.), created previously in the simulation step, and

statistical analysis is conducted to test the hypotheses established. Sensitivity analysis is also carried out at this stage considering two main scenarios – the steady-state and transition. The output from the sensitivity analysis includes operational performance metrics of the scenarios based on the steady-state and transition products, dimensions of flexibility applied at the manufacturing echelon, etc.

With the input from the sensitivity analysis above, the optimization model provides the last stage of the research framework. This stage is explained in section 3.8 and supporting data is available in Appendix F. At this stage, there are two interrelated analyses for optimality - achieving a maximum TH and minimizing cost. Therefore, the inputs to the optimization model are TH and cost computed at the manufacturing echelon, constrained by production capacity, max/min levels of flexibility, and expected demand of each type of product. The optimality model is setup as multi objective model.

If an optimal solution is not achieved at 95% confidence interval, iteration is introduced with another set of inputs (levels of dimensions of flexibility) from the performance systems design stage. That is, an output from the optimization stage is used to determine whether to continue to reiterate through the performance system design or not.

3.2 Class of Supply Chain Based on Manufacturing Flexibility

3.2.1 Characteristics of Supply Chains

The classification of supply chains is complex because of the variability in defining a supply chain. A supply chain system can be classified based on multiple perspectives

including the flow of materials, information, and money along a network of supply chain echelons such as suppliers, manufacturers, distributors, retailers, and end-user customers. In this study, retailer is the customer or the last in the downstream chain. It is therefore necessary to narrow the scope to a specific class of supply chain.

The class of supply chain in this research is referred to by the attributes of the product mix and its impact on each echelon (pre and post the manufacturing echelon) of the supply chain and the logistics between the echelons. This requires that each echelon of the supply chain to be more specific classification by product and supply chain echelon is provided below. This supply chain is referred to as “***Flexible Discrete Supply Chain***” (FDSC). FDSC is different from others for the following characteristics. It addresses supply chain systems characterized by dynamic product demand in a retail specific availability, which for example embraces impulsive purchasing by customers. This requires a discrete manufacturing process to respond to the dynamism of the product volume and mix with either elimination of those not performing well or through enhanced innovation for introduction of new products. The manufacturing system should be flexible enough not only to accommodate the variabilities in raw material ingredients, which are often dependent on offshore supplying partners, but it should also possess the capability to respond quickly to the dynamics in the downstream supply chain system.

3.2.2 Specific Classifications

The characteristics described above provide background for more detailed classification in view of manufacturing flexibility. This requires that each echelon of the supply chain to be classified. More specific classification by product and supply chain echelons is provided below.

Product

- Retail product sold in multiple outlets.
- Dynamic product demand.
- Products are taken off the shelf if customer demand is low.
- High level of product mix.
- High product volume.
- Majority of the components of the product mix are similar.
- New products are introduced every year. These products are integrated in manufacturing with existing products that are identified to continue.

Impact on supplier

- Two suppliers, each supplying dynamic volume of ingredients.
- Dependent on both continental offshore suppliers.
- Long lead times to receive ingredients.

Impact on manufacturing

- Equipment driven manufacturing. Therefore, dependent upon availability of the equipment.
- High frequency of setups to produce high product mix.

- High level of pressure to integrate new products.
- High requirements on quality and yield.
- High expectation to meet delivery dates.
- High level of schedule manipulation.

Impact on distribution

- Multiple localized distribution centers.
- High volume and mix received on distribution centers.
- High level of product control in distribution.

3.3 Performance System Design

3.3.1 Limiting Flexibility Dimensions

An overview description of each of these dimensions was provided earlier (see section 3.1.2), but it is important to recap the scope of the innovation flexibility dimension here. In this study, innovation flexibility is limited to product innovation. Similarly, the importance of limiting the flexibility dimensions into four only is described as follows. Although some literature provides various dimensions of flexibility (for example, see Oke, 2005; Naim et al., 2006; Oberoi et al., 2007), this work is limited to four dimensions of flexibility critical for an FDSC. Suarez et al. (1991) in their literature critique on flexibility and performance indicated the importance of these four dimensions of flexibility: volume, mix, delivery, and innovation. The literature in the domain of manufacturing and operations flexibility describes various areas of innovation such as

product innovation, process innovation, services innovation, or development of new business processes, etc. (e.g., Porter, 2004; Biazzo, 2009).

Section 3.3.2 defines and quantifies each of the dimensions of flexibility and how these dimensions in manufacturing impact the proposed performance of the overall FDSC and each echelon of the FDSC in terms of TH and cost. *This creates a body of knowledge relating manufacturing flexibility dimensions (leading indicators) and FDSC performance in terms of TH and cost (lagging indicators).* This relation is presented in section 3.3.3.

3.3.2 Flexibility Definition and Interpretation

Volume flexibility (VF): It is crucial for the supply chain system to utilize its capacity to accommodate fluctuations in demand. As the demand quantity increases or decreases, this capacity can be adjusted accordingly. Volume flexibility is highly desirable to address dynamic customer demand. In this study, VF is formulated by considering the weight, to indicate the type of product – steady-state or transition; hence a novel approach is introduced. *Therefore, Volume flexibility is defined here as the ability to adjust capacity or availability in relation to the quantity of demand to be met for a specific product type.*

Previous studies have not defined volume flexibility by considering the type of product or priority given to product types. For example, Beamon (1999) defines volume flexibility as a measure of “the proportion of demand that can be met by the supply chain”. *It is important to account for the proportion of demand that can be met,*

especially for an FDSC that is attributed to dynamic demand. But again, the author did not account for a product type.

Demand estimates may be obtained in various ways. One of these estimating methods or approaches depends on historical data of shipments of finished products or processed orders, say as it moves from manufacturing to distribution or to the next echelon downstream. What is resulted from these approaches is a time-series form of estimated outputs. The estimates serve well for certain cases, but if the goal is to capture accurate estimates, especially for products of lumpy and unpredictable in nature, the result would be to the negative extreme – it will not work. *Therefore, introducing a probability estimate as part of the computation serves to handle the issues stated above. The probability estimate takes in to account the maximum and minimum volumes of production along with average demand. Along with the probability estimates, taking the assumption of a normal distribution makes the computation to fit a natural phenomenon, hence close to the actual operating conditions of the supply chain system in general and the manufacturing echelon in particular.* Doing so integrates the manufacturer's preparedness through probabilistic sensing of the demand, to allocate appropriate volume flexibility needed. The value of VF is between 0 and 1, because it is formulated as a probability equation. The closer VF is to 1 is an indication of higher flexibility. Therefore, in equation 3.1, the variable w_{si} , must be between 0 and 1 to meet the above condition.

Within the context of creating VF at manufacturing echelon, the formulations shown in equations 3.1 and 3.2 can be interpreted as the impact of volume flexibility at

distribution echelon because production output is compared against the demand at a time period. Similarly, if incoming quantity from a supplier echelon is compared against the production capacity at manufacturing, this shows the impact of volume flexibility at supplier. From a similar perspective, the costs associated with the changes the volume flexibility has created in the pre and post echelons of the manufacturing echelon are computed and interpreted.

$$VF = w_{si} \times P\left(\frac{V_{min} - D_{avg}}{\sigma_D} \leq D \leq \frac{V_{max} - D_{avg}}{\sigma_D}\right) = w_{si} \times \left[\varphi\left(\frac{V_{max} - D_{avg}}{\sigma_D}\right) - \varphi\left(\frac{V_{min} - D_{avg}}{\sigma_D}\right)\right] \quad (3.1)$$

$$D_{avg} = \frac{\sum_{t=1}^T d_t}{T} \quad (3.2)$$

Where

P : probability

D : Volume of demand is a random variable. Assume it can be approximated using normal distribution with mean, μ_D and standard deviation, σ_D

D_{avg} : Average volume of demand during period t , $t = 1, \dots, T$

d_t : Volume of demand at period t

σ_D : Standard deviation of volume of demand

φ : Normal probability function

V_{max} : Maximum volume output

V_{min} : Minimum volume output

w_{si} : Weight assigned to product type (steady-state or transition) s , for flexibility dimension i .

V_{max} and V_{min} are outputs determined based on “**production reliability**” (**PR**) defined at the manufacturing echelon. PR is a terminology often used in discrete manufacturing (Khodabandehloo & Sayles, 1986; Pereira de Carvalho & Barbieri, 2012), which refers to the theoretical percentage of capacity allocated to meet a minimum production run, hence V_{min} . *The minimum PR is set at 65% based on empirical study. However, again this must change depending on which type of product is being processed.*

Delivery flexibility (DF): On-the-shelf availability is one driving force that prompts customers to buy products in FDSC domain. That means customers are sensitive to timely delivery of products. *Delivery flexibility represents the percentage of time a customer waits for a product if it is not available.* This is based on the definition: “delivery flexibility is the ability to change delivery dates” (Slack, 1991; Beamon, 1999).

Delivery flexibility as formulated in equation 3.3, is represented by the ratio of the difference between customer due date and earliest time, and the difference between customer due date and current time. *Therefore, the higher the DF, the better flexibility in the system would be.* For example, if a minimum and maximum process time at the manufacturing echelon is known, and the inter-arrival times from supplier or the lead times of sourcing raw materials are determined, supplier delivery flexibility (note: the manufacturing echelon is the customer to the supplier echelon) can be computed as the ratio of the difference between longest delivery time and shortest delivery time, and longest process time and current arrival time. Similarly, from manufacturer to distributor

and distributor to the next customer in the downstream of the chain, their respective DF can be computed and their impact to TH and cost is interpreted accordingly.

$$DF = \mathbf{w}_{si} \times \sum_k^K \frac{(L_k - E_k)}{(L_k - t)} \quad (3.3)$$

Where

E_k : Earliest possible time to deliver item k , $k = 1, \dots, K$

L_k : Latest possible time to deliver item k , $k = 1, \dots, K$

t : the time when an order is received or the current time.

L_k should be greater than t , to avoid negative value of DF, which would mean that there is backorder. Since L_k is the latest time to deliver, it can be assumed as a customer's due date.

$$L_k > t \quad (3.4)$$

Again, including the weight for a product type as shown in equation 3.3 is a unique formulation to help distinguish or provide priority by product types.

Mix flexibility (MF): Customers' dynamic demand choices require the flexibility to handle heterogeneous products. Customer demand can be seasonal causing a mingled problem (i.e., product variety and seasonality) to the dynamics of the product. MF is "the ability to change the product mixes in current production" (Parker and Wirth, 1999), which enables the supply chain system to cope with such changing customer behaviors and trends. MF can be interpreted as the number of sets of product types produced in each period or the ability to switch production from one product type to another. The latter is called "product mix flexibility response" (Slack, 1991; Wahab, 2005). *MF is measured in time units as the changeover time needed between two*

consecutive products types. Equation 3.5 is formulated by introducing a constant coefficient or weight to distinguish between steady-state and transition products.

$$MF = w_{st} \times \sum_{k=1, k \neq l}^n C_{kl} \quad (3.5)$$

Where

C_{kl} : Changeover time required between products k and l .

$$C_{kl} \geq 0 \quad (3.6)$$

Innovation flexibility (IF): FDSC domain exhibits changing trends, where some or all of products are subject to obsolescence. Many production systems must replace obsolete products with new products in a production cycle or taken out of production in the next production cycle. This introduction of new products is a criterion to use innovation as one key dimension of flexibility. Innovation flexibility is the introduction of new products to the existing product mix or creating a new set of product families to enhance sales. *It is measured by the number of new products (usually counted by SKUs) added to the existing products during the existing production cycle. It can be referred to as the schedule of introducing the new product (termed here as “innovation schedule”) during the current production cycle.*

Introducing a new product requires extensive setup time and development time. Development time refers to the time it takes from sensing the need for the introduction of new product, based on product life cycle, to going through test runs before an actual product is configured in an existing facility. Equation 3.7 shows the total number of new products innovated in a designated time. As discussed later in section 3.6, such products will have extensive pre-build.

$$IF = \frac{\sum_{t=1}^{P_c} N_t}{P_c} \quad (3.7)$$

$$P_c > 0 \quad (3.8)$$

Where

N_t : Number of items introduced at time t , $t = 1, \dots, P_c$. t is the time when obsolete products are designated or where the time when new product introduction starts.

P_c : The maximum production cycle during which add new products can be added to the existing products. For example, if P_c is a year and new products are scheduled to be introduced say in January, February, and May, equation 3.7 provides the total number of units or SKUs introduced per year. Note: a constant coefficient or weight is not included in equation 3.7 because the product type is already known to be a transitional or new product.

3.3.3 Defining Performance Measures

In this section, the supply chain performance measures introduced above are integrated with key metrics – leading and lagging indicators. These include the leading indicators such as setup time or changeover time, batch size, customer date, etc. used to measure VMDI, which in turn impact flow, disruption, and variation. Flow, variation, and disruption are referred to here as the three ***dimensions of Cycle Time (CT)***. As discussed in section 3.1.1, *CT impacts TH based on Little's law. This implies that if the TH_{mfg} and CT_{sys} would similarly be obtained about the manufacturing echelon and the supply chain as a system.* TH in turn impacts customer service level (an indicator that shows if the proportion of demand met is acceptable, lags, or exceeds customer

expectations) and cost. Therefore, the lagging indicators are initially TH, and subsequently cost and service level (if applicable).

These lagging indicators are used to investigate the impact of the flexibility dimensions on the echelons of the FDSC, especially those immediately pre and post the manufacturing echelon. For example, the role of volume flexibility will be evaluated on FDSC performance as a system, to TH and cost from manufacturing, its impact to the supplier echelon and distribution echelon, etc. along other echelons of the FDSC. Similarly, innovation flexibility as described in previous section (see section 3.3.1 for different types of flexibility related to innovation) is used to address the issues of short product life cycle, hence the focus is on product flexibility. *On the other hand, innovation may be treated as disruption. It requires additional setup time to be introduced or change in scheduling to other products so that the production equipment can be used to develop new products.*

The leading and lagging indicators of FDCS performance is provided graphically below. *Figure 3.2 builds on a framework illustrated by Sawhney et al. (2019). Here, the dimensions of CT, VMDI and corresponding performance metrics in VMDI are integrated into the previous framework, which is the interest of this study in defining performance measures.* Besides the presentation of lagging and leading indicators in figure 3.2, an additional illustration should be provided to allow visualizing a detailed understanding of the impact of flexibility on TH of the FDSC using sets of possible metrics. However, although they are required in a simulation setup, not all these metrics are controlled in the simulation model. This implies the need for further development of

a relationship between the metrics that need to be controlled and VMDI. A simplified version of Quality Function Development (QFD) is used to create a relationship. *Here, it is important to emphasize that leading indicators are coming out of the QFD and the lagging indicators are obtained from simulation. In other words, the simulation metrics are associated with QFD.* The subsequent figures and tables in this section are used to illustrate the above relationships.

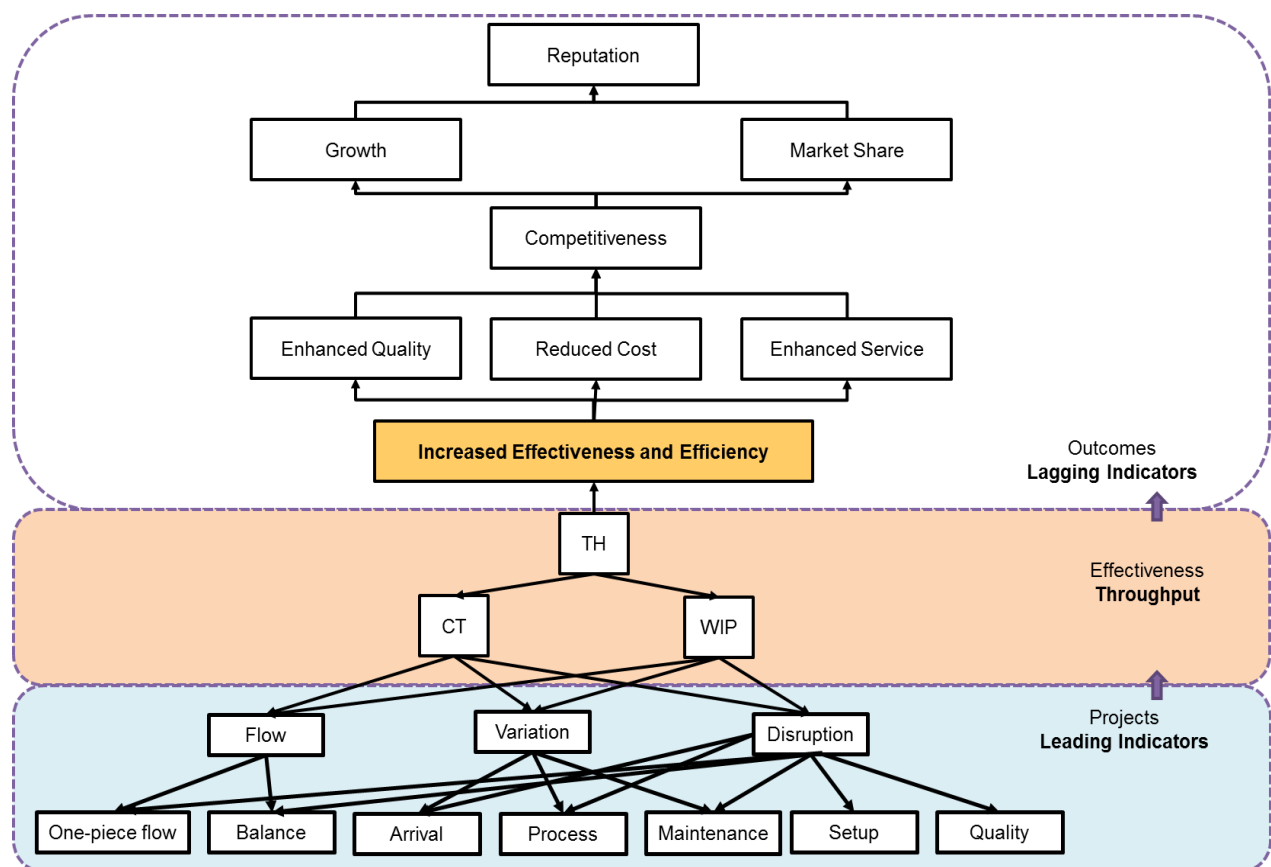


Figure 3.2: Leading and lagging indicators of FDSC

As described above, the framework provided in Figures 3.2 requires further illustrations through mapping of the VMDI to potential metrics that need to be prioritized later using QFD. Figure 3.3 shows these metrics. The information provided in Figures 3.2 and 3.3 lead to the development of a relationship matrix encompassing the VMDI and the three dimensions of CT and align them to the research hypotheses. The relationship is developed by taking the research hypotheses into account (see section 3.1). QFD is a matrix (e.g. see Table 3.1) which helps to translate customer requirements or voice of the customer into technical requirements (e.g. see Matzler and Hinterhuber, 1998; Chan and Wu, 2002; Chang, 2012).

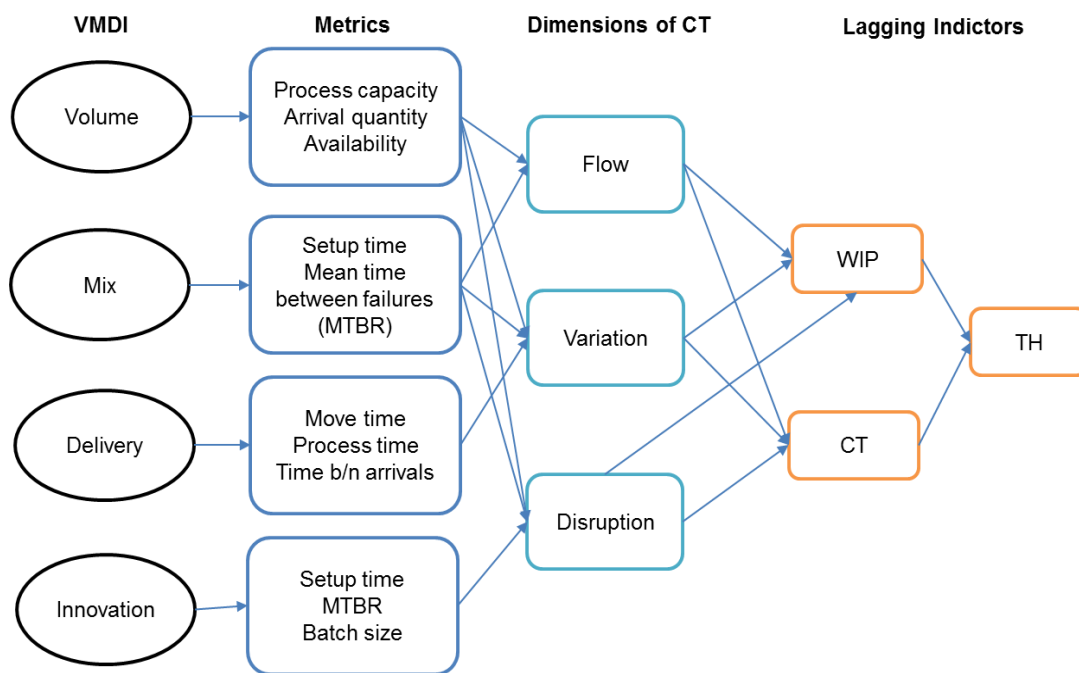


Figure 3.3: Detailed performance metrics

It is not the interest of this research to describe what QFD is. *Instead, in this study, the primary purpose of using QFD is to translate the dimensions of flexibility to key metrics that can be controlled in the simulation model.* If all the metrics identified in Figure 3.2 and 3.3 are considered, it would lead to creating multiple matrices from HOWs vs. WHATs and HOWs vs HOWs of the QFD settings. However, the focus here is on key metrics. The following steps are used to develop the QFD.

- 1) Identify metrics or attributes used to describe dynamics of demand at the retail end of a supply chain (from section 3.2). To understand the relative importance of these attributes and/or metrics a scale of 1 to 5 is used.
- 2) Identify the metrics corresponding to the dimensions of flexibility used as technical requirements to meet customer needs and hence to enhance TH and reduce cost (from figures 3.2 and 3.3).
- 3) Develop relationships between steps 1 and 2 and evaluate the relationship matrix. A three-point scale of 1, 3, and 9 is used to denote a weak (+), moderate (++), and strong (+++) relationship, respectively. A value of zero or if matrix is left blank, it denotes no relationship. For negative relationships, -1, -3, and -9 is used to denote a weak (-), moderate (--), and strong (---) relationships, respectively.
- 4) Construct a correlation matrix of the dimensions of flexibility. A three-point scale of 1, 3, and 9 is used to evaluate the matrix. Similarly, negative relationships are represented as mentioned in step 3 above.
- 5) Evaluate the relative importance of the metrics in relation to their impact on TH and Cost, using a scale of 1 to 5.

Following the above steps, tables 3.1, 3.2, and 3.3 (see page 58-59) are created to illustrating how the VMDI are translated into key performance metrics which are controlled in the simulation model. *The basis of the information for completing the tables is empirical and literature driven (e.g. see Esturilho and Estorilio, 2010). However, the authors used different dimensions of flexibility.* The last two rows in each of the tables 3.1, 3.2, and 3.3 provide scores. But these are for illustrations only. For example, in table 3.1, it shows that considering all the customer attributes or requirements, the primary flexibility dimension that needs attention would be volume, followed by delivery. Similarly, table 3.2 is used to narrow down the list of metrics into key metrics that can be controlled in the simulation, which are reduced to four in table 3.3. *In other words, key metrics that need to be deployed are identified using QFD.*

Table 3.1: FDSC planning – matrix 1

Examples of customer requirements	Volume	Mix	Delivery	Innovation
Fill rate (service level)	+++		+++	
Retail specific delivery to multiple outlets	++	+++	+++	
Accurate order size	++		+	
Dynamic demand	+++	+++		+++
On shelf availability	+	+	+++	
Short product life cycle		++		+++
Feature raw score	33	27	30	18
Feature rank	1	3	2	4

Table 3.2: Relationship of VMDI metrics – matrix 2

VMDI	Examples of metrics								
	Equipment availability	Process capacity	Setup	Customer date	Schedule	Product life cycle	Move time	Process time	Quantity moved/produced
Volume	+++	+++	+					+	+++
Mix	+		+++			+		+	+
Delivery	+			+++	+++		+++		
Innovation	+	+			++	+++			+++
Feature raw score	18	12	12	9	15	12	12	6	21
Feature rank	2	4	4	5	3	4	4	6	1

Table 3.3: Lagging indicators relationship to key metrics – matrix 3

Lagging indicators	VMDI - metrics			
	Equipment availability	Setup or changeover	Schedule	Quantity moved/produced
TH	+++	+		+++
Cost	+	---	+	---
Feature raw score	12	-6	3	0
Feature rank	1	4	2	3

Following the presentation of the definitions of the dimensions of flexibility and integrating them to lagging indicators, the next step is to conceptualize a supply chain setup. In the supply chain setup, the sets of performance metrics are configured.

3.4 FDSC Setup

3.4.1 Configuration of FDSC

The performance metrics identified and prioritized in the previous section as part of the performance system design would serve no use unless they are configured to a well-designed supply chain. The FDSC setup is the supply chain design that integrates these metrics. By supply chain setup, it is meant to refer to the composition of the supply chain in terms of the echelons it comprises, from sourcing of ingredients or raw materials to manufacturing and distribution of finished products, and the networks involved in each echelon (whenever applicable).

In FDSC, this research assumes a four-echelon supply chain system: supplier, manufacturer, distributor, and retailer/customer, containing one to two nodes in each echelon. When the dimensions of flexibility are applied at manufacturing echelon, it leads to measuring the impact of flexibility on the remaining echelons. That is, the FDSC setup emphasizes on conceptualizing the impact of manufacturing flexibility on the supplier, distributor, the supply chain system, etc. This was briefly mentioned as part of definitions and interpretations of dimensions of flexibility in section 3.3.2 above. It is discussed here in more details. Therefore, it is imperative to start with a conceptual setting.

3.4.2 Conceptual FDSC

The supply chain is impacted by the levels of the flexibility dimensions. Some (echelon, dimension) combinations may not be impacted. This idea is presented in Table 3.4. Cells which show some marks are impacted; those with 'NA' are not impacted. Let v_{11} represents flexibility dimension 1 (volume) for product type 1 (steady-state). The value of the first cell to the left in the supply echelon, represents the TH and Cost impacted because of v_{11} .

Figure 3.4 shows a supply chain structure represented by blocks and flows, and some of the assumptions or attributes corresponding to each echelon. In reference to figure 3.4, the lagging indicators that would be impacted because of applying are “quantity moved” and “cost of moving” respectively. Moreover, the varieties of ingredients for raw material from the first block (supplier) are identified by specific quantity, quality, and frequency of arrival and the cost of freight to the second block (manufacture). Such representation is consistent with the simplified ways to present complex systems as defined by Hopp and Spearman (2011). It indicates multiple suppliers to the manufacturer, which then supplies to a single distribution entity. The retail entity is assumed to be the final customer. Because of the variety in product type and product quantity, the retail entities are limited to two major categories for simplicity.

Figure 3.5 shows an example of a supply chain system, which contains two suppliers, a manufacturer, a distributor, and two retailers. It is used as a basis for experimentation and simulation. The figure illustrates the input to the manufacturer, where the process of manufacturing flexibility is carried out, and output from the

Table 3.4: Conceptual supply chain

VMDI	Supply Chain Echelon							
	Supply		Manufacturing		Distribution		Customer	
V	✓	✓	v_{11}	v_{12}	✓	✓	N/A	N/A
M	✓	✓	v_{21}	v_{22}	✓	✓	✓	✓
D	✓	✓	v_{31}	v_{32}	✓	✓	✓	✓
I	✓	✓	v_{41}	v_{42}	N/A	N/A	✓	✓

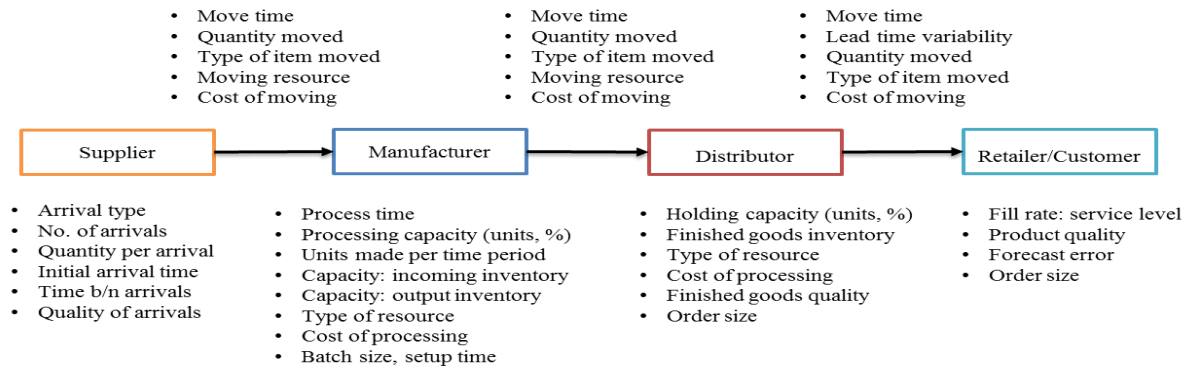


Figure 3.4: A supply chain process – blocks and flows

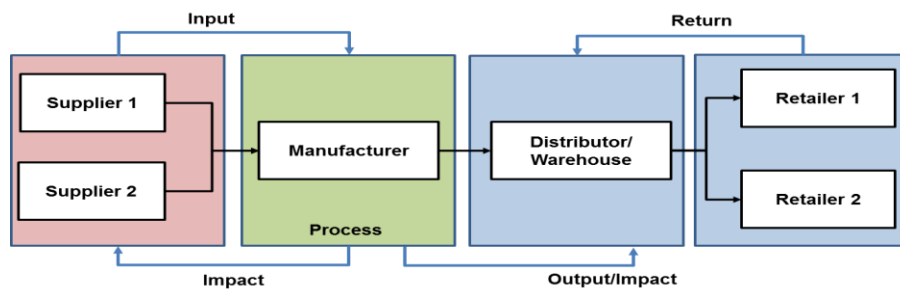


Figure 3.5: FDSC system

manufacturer and the impact of flexibility to other echelons, as well as other factors to be considered such as reverse logistics of obsolete products from downstream side of the supply chain. With the supply chain clearly defined and classifications provided, the performance system designs identified and prioritized, and the conceptual FDSC setting described, what follows is an illustration of the experimentation and setting up simulation modeling based on the information discussed above.

3.5 Experimentation

3.5.1 Introduction to Design of Experiments and Data Collection

Based on the conceptual structure illustrated in the previous section, dimensions of flexibility and defined performance measures, and quantitative models related to the VMDI described above, what follows is experimentation. This section focuses on the actual experimentation process. That is, the use of design of experiments (DOE) to setup the experiments for determining the impacts of manufacturing flexibility.

The experimentation process involves multiple sets of scenarios, at three levels of each flexibility dimension, subject to the leading indicators mentioned previously (see section 3.3.3), and the simulation process is run under three configurations for two products types. At this stage, back and forth iterations between running an experiment and collecting data through simulation are the major process. The simulation modeling setup is a standalone section and is discussed further in section 3.6. Following this brief introduction to DOE, the objectives of the DOE is discussed next.

3.5.2 Objective of Experimental Design

The impact of the dimensions of flexibility on TH and cost cannot be fully examined without a properly designed experiment. A carefully planned DOE clarifies which set of variables in a process affect performance the most and enables to determine the best levels to obtain satisfactory output (Antony, 2014; Anderson and Whitcomb, 2016). In addition, any DOE must start with a clear problem definition and determining objectives. The next major steps after the objectives are set to include designing the experiment, conducting the experiment, and collect data from different scenarios.

The experimentation process used in this study is compliant to a typical experimental design, which involves about eight process stages. These stages are like a scientific problem-solving process. It includes problem definition, determining objectives, brainstorming, design experiment (i.e., selecting a design for screening factors or for actual experimental run from a factorial, response surface, mixture, or Taguchi types of DOE), conducting an experiment and collecting data, analysis of data, interpretation of results, and finally verification of predicted results or making inferences for general conclusions based on specific results.

3.5.3 Selection of Design Parameters and Determining Levels

The experimental design is constructed for the four dimensions of flexibility—volume, delivery, mix, and innovation (VMDI) using a three-level (high, medium, low) design per factor, which are defined to indicate three configurations (more in section 3.6.1).

Simulation outputs such as average TH, CT, WIP, and average total supply chain cost are obtained in each scenario.

An example of the settings of parameters and levels is shown in Table 3.5. As defined in section 3.3, the volume flexibility should be between 0 and 1. Two conditions were indicated to satisfy this condition. The first one is the weight assigned for the specific type of product (either a steady-state or transition). The second condition is the probability function that considers the average demand, standard deviation of demand, and maximum and minimum demand volume, as shown in equation 3.1 and 3.2. For example, if the data given in table 3.5 for volume is used as input, the VF at each level can be determined. Similarly, the delivery times are given at each level, but the expected due date must also be known, and the weight assigned for the type of product set to compute the DF. As formulated using equation 3.5, mix flexibility is a function of setup or change over time, so the experimental levels can easily be illustrated using the maximum, medium, and minimum time it takes to carry out the setup.

Table 3.5: Quantifying VMDI levels

	Volume (x1000 of SKUs)	Delivery (hours)	Setup (minutes)	Innovation (schedules per year)
Level 1: Low	10	4	9	0
Level 2: Medium	18	6	6	2
Level 3: High	36	8	5	4

But again, for these levels to be useful for an FDSC experimental setting to set MF, the type of product's weight is important. The innovation schedule, shown in the table may be used directly to represent the levels of innovation flexibility assuming year as the horizon for evaluation of flexibility.

Another important consideration when selecting design parameters and levels in any supply chain, including the FDSC is to dictate an inventory policy. For this experimental setting, the inventory policy between the sequences of echelons is assumed to be fulfilled periodically with predetermined minimum and maximum stock levels at the retail end. As such, this experimental design must control the inventory policy.

3.5.4 DOE's Interaction Effects, Response, and Design Approach

In this experiment, the interaction among the factors is also considered. Without evaluating the interaction impact of two or more of the dimensions of flexibility, it would be difficult to prioritize which dimension should be applied and when to enhance TH or reduce cost or to find an optimal point where a balance between TH and the minimum cost is reached. To better understand an experimental design's output results and the interpretation of these results, studying the factors' interaction effect is crucial (Marilyn, 1993). The simulation model's outputs are used within DOE to further investigate details and to understand the interaction among the dimensions of flexibility, which are continuously reiterated to obtain a maximum TH. The simulation model setup and configurations are discussed in detail later in section 3.6. Beamon and Chen (2001)

used a similar approach – integrating simulation and experimental design, but with different sets of factors and hence for a very different performance optimization.

There are different ways of creating an experimental design, including full factorial design, fractional factorial design, Box-Behnken Design (BBD), etc. Selecting anyone of these DOE methods depends on various reasons, such as the number of factors, number of levels, desired numbers of runs, availability of supporting resources (e.g. time, cost, expertise, etc.). Cavazzuti (2012) provides a sample of the various types of experimental design methods. A tabular form is presented in Table A.6, where each of these methods is compared based on the number of runs needed and the suitability of each design in applications. According to Ferreira et al. (2007), BBD is effective as compared to central composite design (CCD) and a full factorial design when dealing with experimental design of three or more factors. In addition, according to Myers et al. (2016), BBD is more commonly used in response surface methodology (RSM). *Therefore, BBD is used for experimental design in this study.* Then, the optimal results obtained from an RSM is compared to those computed using simulation optimization, more specifically an evolutionary algorithm which is used in a plug-in optimization software called SimRunner, that comes along with ProModel simulation software. The impact of this relationship and comparison is discussed later in section 3.8 and subsequent sections.

Tables 3.6 shows the BBD setup. *Table A.8 in Appendix A, shows a Box-Behnken Design (BBD) of the dimensions of flexibility at three levels each.* The table shows the experimental design, for a single replication only. However, selecting an

appropriate experimental design alone is not enough to obtain performance outputs in such a DOE – simulation synchronized approach. Experimental conditions for simulation runs must be established before the expected performance measures are analyzed. Thus, the next section deals with simulation modeling.

3.6 Simulation

3.6.1 Simulation Setup and Tools

The simulation design/setup includes the number of replications and the number of runs. For this simulation setup, the number of replications is determined using the confidence interval method (Law and McComas, 1990; Robinson, 2004; Banks et al., 2005; Law, 2007) as illustrated below. The confidence interval method is statistically more justifiable as compared to other methods. The literature provides other commonly used methods to determine the numbers of replications such as the rule of thumb approach and the simple graphics (Robinson, 2004).

Table 3.6: Summary of BBD

Factors:	4	Replicates:	1
Base runs:	27	Total runs:	27
Base blocks:	1	Total blocks:	1
Center points:			3

Based on the rule of thumb, 3-5 replications would suffice regardless of the complexity of the simulation model to obtain a rough estimate of performance outputs. In the case of the simple graphical method of validation, model output and available data are compared graphically.

- 1) Assume an initial run of $n_0 = 10$ replicates

$$\bar{x} = 32990.20, h_0 = 7335, s = 10300$$

- 2) Find the student t -test critical value for 95% confidence interval ($\alpha = 0.05$)

$$t_{10-1, 1-\alpha/2} = 2.262$$

- 3) Compute half-width, h

$$h = \bar{x} * 0.05 = 1649.51$$

- 4) Calculate the optimal replication, n :

$$n = \frac{n_0 h_0^2}{h^2} = 197.77 \approx 200$$

The simulation should run for a longer period (e.g. at least a year) in order to capture the product characteristics of the FDSC and to provide extrapolated data depending on three types of configurations (corresponding to inventory levels and frequency and number of disruptions) and two classes of products. These configurations as shown below align with the experimentation setup represent high, medium, and low levels of flexibility, respectively. Experimentation was discussed in section 3.5.

- 5) Configuration 1: No inventory

$$\text{Total Supply Chain Cycle Time (TSCT)}_{max} = 250 \text{ days (to get 1st lot)}$$

6) Configuration 2: Partially charged (when faced unexpected disruptions). $T_{SCT_{mod}} = 30 - 80$ days.

7) Configuration 3: Fully charged (quick request of all inventories). $T_{SCT_{min}} = 30$ days.

Since computer-based simulation is a broad field, the focus here is on using discrete-event simulation (DES). DES is suitable for modeling systems whose system's state changes at a time and then remains in that state for a distinct time period. One of the biennial surveys by Swain (2013) on DES software provides evaluation metrics such as product's capability, special features, and usage. There are several simulation software packages depending on the problem at hand where they are applied. For reading a detailed summary of the types of simulation software used in the supply chain context, see the literature review by Terzi and Cavalieri (2004). In this work, the software used, that is, the simulation tool is ProModel® (Promodel Corporation, 2015). ProModel® is powerful and at the same time easier to use tool for various types of manufacturing systems and supply chain systems (Benson, 1997; Harrel and Price, 2000 and 2003). Regardless of the type of DES software used, there are commonly accepted procedures that can equally apply to any simulation setup. The following steps are used to setup the simulation.

1) Formulation of the problem - description of model objectives. In this case the objective of the simulation model is to serve as a data collection tool from various simulation runs mainly for two major scenarios pertaining to the steady-state and transition products.

- 2) Identification of independent and dependent variables. The attributes and variables indicated in Figures 3.2 and 3.3 are used as input variables or independent variables for collecting data on TH at the manufacturing stage, TH at supply chain level, and total supply chain cost. TH and cost are the two competing maximization and minimization response variables, respectively.
- 3) Data collection. At this step, data from the simulation model runs are collected. Outputs are the lagging indicators described in section 3.3 above.
- 4) Verification and validation of model results based on the data collection stage above. As described in the next chapter the type of simulation model validation is called a *face validation* because an actual case study was used for validation of results.
- 5) Analysis and documentation of results. At this step, the outputs from the validated model are used to conduct further analysis.

A validated simulation base model is the primary phase. Then follows a detailed scenario analysis based on the DOE defined previously, and to create additional data for statistical analysis as well as to formulate an optimization model using the plug-in optimization tool, as subsequent phases. The steps described above along with the configurations by product type (discussed in section 3.6.2) are used to create the simulation setup, in other words, to serve as the simulation strategy.

3.6.2 Configuration for Steady-state and Transition Products

In reference to the configurations described in terms of TSCT, the ‘no inventory’ configuration refers to the transition product scenarios. The dimension of flexibility that has significant importance in the transition scenario is innovation flexibility. In the simulation setup, the innovation flexibility will be characterized by higher warm-up time because practically, new product developments need additional pre-build (or setup) time and adjustments to existing equipment to configure it suitable for the new product. Configurations 2 and 3 above are mainly for steady-state products, hence, mainly volume flexibility, delivery flexibility, and mix flexibility would be more applicable.

Since transition products as described above are supposed to take much longer time in setups, training personnel, etc., the weight used for a warm-up time must be determined. There are several methods to determine the warm-up time (Law and Kelton, 2000). The authors suggested that the easiest method is called the “Welch Method”, which requires a preliminary simulation run of the system on average 3 – 5 replications after the system reaches a steady-state. But to make sure there is more statistical stability a 20 – 30% safety factor is recommended (ProModel, 2012). *This safety factor is used in this study to show the levels of weight assigned to transition and steady-state products.*

One of the most important applications of simulation is the comparison of alternative scenarios in the form of a simple DOE. However, it requires statistical analysis to determine whether any observed differences result from differences in the solutions or to the simulation model’s inherent randomness (Banks et al., 2000). *An*

experimental design using software specifically designed for DOE complements the simulation model, by taking the “What if” scenarios into a more statistically intuitive analysis. The two competing objectives are the maximization of TH with a minimal cost.

3.7 Statistical Analysis

This section focuses on data analysis. Initial analysis of the simulation results is provided. Although statistical reports on the performance indicators (the lagging indicators thoroughly discussed above, see section 3.3) can be obtained at the end of every simulation run, Minitab software is used for further statistical analysis. Then, a detailed sensitivity analysis is presented before the optimal solution is determined. Multivariate analysis, testing the hypotheses and validating and inferences of the hypotheses are included.

3.7.1 Regression Analysis

Regression analysis is used in this study for two important reasons. First, regression analysis helps to predict the effect of the dimensions of flexibility on the response variables (TH and cost) depending on the amount or level of flexibility utilized. Second, it enables to infer the forms of relationships between the dimensions and the specific response. Regression analysis is needed in order to model the response variable as a mathematical function. It makes it an objective analysis of the response by changing the independent variables or simply the coefficients of the independent variables show in which direction and the amount the response can change or it regresses.

Since there are two response variables and more than one independent variables – the dimensions of flexibility, plus the configurations corresponding to the types of products, the relevant way of exploring the quantitative relationship between the variables is a multivariate regression model. The form of the regression model can be linear or nonlinear (e.g. quadratic). However, the DOE model found appropriate to this study is BBD, which provides enough design for a quadratic regression model. A detailed discussion on BBD is given in section 3.5. An example of a quadratic regression model is shown using equation 3.9. BBD is more commonly used in response surface methodology (RSM), where the response variable displays a curvature form of relationship.

$$Y = \beta_0 + \sum_{i=1}^k \beta_i x_i + \sum_{i=1}^k \beta_{ii} x_i^2 + \sum_{i=1}^k \beta_{ij} x_i x_j + \varepsilon \quad (3.9)$$

Where, Y is the response variable, $x_1, \dots, x_k$ are the factors, and β_0 and β_i coefficients, ε represents the error.

3.7.2 Hypothesis Testing

With four dimensions of flexibility implemented at the manufacturing echelon and then impacts observed at the echelons prior and post the manufacturing echelon, this results in 16 variables to be tested, including the immediate output from the manufacturing. The FDSC system includes four echelons. The effectiveness or usefulness of these variables is validated via the output obtained as either a maximum TH or minimum cost.

To do this, different values of TH and costs are obtained at various configurations or settings of these variables. Configuration of FDCS was described above (see subsection 3.4.1). For example, TH_{VF} , TH_{MF} , TH_{DF} , TH_{IF} , corresponding to TH resulted from volume flexibility, mix flexibility, delivery flexibility, and innovation flexibility respectively are compared. However, statistically, the viable approach is to make a comparison of their mean values. Therefore, in this study, the least significant difference (LSD) method is used for the comparison of the mean performance measures (for both TH and cost). The formulation of the null and alternative hypotheses was discussed in subsection 3.1.1.

3.8 Optimization

Two approaches are used to study the optimality. First, as a continuation of the statistical analysis, a response optimizer is used to identify the combination of input variables settings used to evaluate the optimality of one or more multiple responses. The second approach is simulation optimization. Deploying these two approaches creates a further strengthen validation and compare the optimal results.

To measure the optimality of a supply chain system, there can be various performance indicators; for instance, the key measures can be delivery and cost-based metrics. For this work, total supply chain cost measures the optimality of the amount of TH obtained by the end-customer.

This research presents the model optimization of TH by integrating flexibility as a design dimension for the performance of a four-echelon and multi-product supply chain

system. A relationship that integrates the four dimensions of flexibility: volume, mix, delivery, and innovation (VMDI) to the three dimensions of CT (flow, disruption, and variation), and TH and cost (lagging indicators), was presented above in section 3.3. what follows next is optimization model formulation followed by the technique and process used to solve the optimization problem.

3.8.1 The Flexibility Model Formulation

In connection to quantifying the dimensions of flexibility, presented in section 3.3 and other relevant variables introduced in this section, and to formulate objectives and constraints, some key parameters are defined as follows. The average costs per time period in major operations in the manufacturing echelon are also formulated.

$F_{i(mfg)}$: Flexibility i , (from VMDI) used at the manufacturing (mfg.) echelon

$CMEL$: Average cost per period t in melting

$CMIX$: Average cost per period t in mixing

$CMOL$: Average cost per period t in molding

$CPAC$: Average cost per period t in packaging

$CRAW$: Average holding cost per period t of raw materials

P : Average product cost per unit u , $u = V_{min}, \dots, V_{max}$

T : Total number of periods

TC_{sys} : Total cost of the supply chain system

TH_{sys} : Total TH of the supply chain system observed at the customer end.

TH_r : TH at retail r (customer echelon), $r = 1, \dots, R$ (total number of retailers or customer echelons)

TH_{mfg} : TH at manufacturing echelon

TH_{dis} : TH at distribution echelon

TH_t : TH at period t , $t = 1, \dots, T$

Objective function

This study addresses a multi-objective function: minimizing total cost while maximizing TH. The supply chain performance is determined to obtain optimal outputs, TH, constrained by total supply chain cost in an FDSC system.

a) Minimize

$$TC = F_{i(mfg)} \times (\sum_k^K (\sum_t^T (CMEL + CMIX + CMOL + CPAC + CRAW) + \sum_{u=V_{min}}^{V_{max}} P)) \quad (3.10)$$

b) Maximize

$$TH_{sys} = \sum_{r=1}^R TH_r = TH_{mfg} + TH_{dis} \quad (3.11)$$

Constraints

$$\sum_{k,t}^{K,T} TH_t \geq \sum_{k,t}^{K,T} d_t \quad (3.12)$$

$$V_{\max(mfg)} \geq TH_{t(mfg)} \geq V_{\min(mfg)} \quad (3.13)$$

The decision variable here is the amount and type of flexibility used and where it is used. It may be noticed that some cost coefficients are combined. This is done for brevity and to easily match with the cost information from a case study. Equation 3.12 shows that the TH expected from the manufacturing echelon should be within the production capacity. Similarly, capacity constraints are applicable to each echelon.

3.8.2 Techniques and Procedures

To conduct optimization, a simulation model is developed and viewed as a black box, where a set of values for input factors are chosen, and the responses generated from the simulation model are used to make decisions for selecting the next trial solution (April, 2003). The optimal solution is generated based on the heuristic algorithm. A heuristic algorithm is inherent in many simulation optimizations packages (Carson, 1997). There are varieties of optimization packages which are designed as plug-in modules added to basic simulation platforms. For example, OptQuest optimization is used in Arena and Simul8, simulation software while ProModel uses SimRunner. List of available options can be found in the studies by Fu (2001) and Swisher (2000). In this study, SimRunner is used for brevity. Figure 3.6 shows the simulation – optimization process. The basic steps of simulation – optimization is listed as follows. The steps are illustrated in more detail in chapter five, where the results and discussion are presented.

- a) Develop and validate the model
- b) Create scenarios
- c) Run the model to create an initial image of what the outputs indicate
- d) Open SimRunner
- e) Set up the target or define the objective function. The objective is to maximize the total entity discharged using a minimum available resource.
- f) Setup the range of elements to be adjusted in the model. These elements are the decision variables.
- g) Select an optimization profile, setup run length and replication

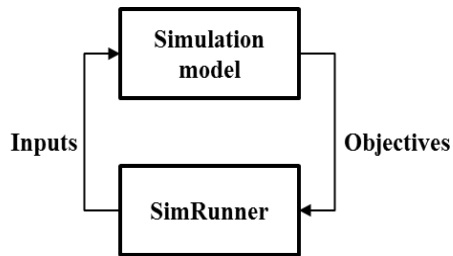


Figure 3.6: Simulation based optimization

Based on the above steps, the simulation optimization is run, and an optimal solution is reached. Here, it is worth mentioning how optimality is determined. It is based on an evolutionary algorithm which allows enables to see the best results and build around that experiment. When the results generated are not good, it gets ride off them.

The steps described above are repeated to test the sensitivity of the objective functions to ranges of values of the decision variables (dimensions of flexibility). The ranges of values correspond to the three levels of each dimension. The other consideration in this analysis is the two main scenarios on product type – the steady-state and transition. Conducting multiple scenarios representing the product type and dimensions of flexibility enables to explore the sensitivity of the objective functions to product type and to understand which combinations of dimensions would result in the optimal solution.

3.9 Summary

In summary, this chapter presented the structure of the research by revisiting the major areas. After laying out the research framework and the motivation behind it, a specific

class of supply chain called an FDSC was characterized. To explore the impact of manufacturing flexibility (dimensions of flexibility applied at the manufacturing echelon) in the FDSC environment on other echelons (prior and post the manufacturing echelon), a performance system was designed. The dimensions of flexibility along with their metrics that can be controlled in a simulation setup are defined. These constitute the independent variables. The dependent variables are TH and cost. Next, the DOE setup using the BBD approach was introduced, which led to the configuration of a simulation model for data collection.

The data obtained from simulation runs requires statistical analysis to study whether the research hypotheses are valid or not, and if valid, how significant is the validation – acceptance or rejection. For this purpose, a multivariate regression model was introduced to enable a prediction of the impact of flexibility on TH and Cost.

Following a statistical analysis, what comes next is an optimization where the mathematical models are formulated to find an optimal solution for a multi-objective function – maximization of TH and minimization of costs. were presented. The 6-phase research framework would serve only as a theoretical foundation that is awaiting proof of concept. This means, in order to be implementable, it must be validated using a case study. Therefore, Chapter 4 is used to prove the validation of the methodology.

4 Validation

4.1 Relevance of the Case Study

A specific case study is utilized to validate the role of flexibility in manufacturing and its impact on maximizing TH. There are multiple mechanisms for validating a concept such as flexibility. Validating via a case study connects this research to the complexities of the industrial world and enhances the practical contributions of this research.

The case study is based on a cosmetics/lipstick supply chain (LSC) as it best meets the criteria established for an FDSC. In the LSC business, there are often many partners involved in the process starting with sourcing raw materials (e.g., shades), packaging materials, and ends with the delivery of final products onto the retailer's shelf. Hence, coordinating the LSC is critical to address the volatility of the business environment. This again ascertains the relevance of LSC case study to an FDSC.

LSC presents an ideal situation where the customer demands, or the types of products sold dictates the performance of its supply chain. To enhance the performance of its supply chain, this multinational cosmetics manufacturer seeks to address global supply chain issues dealing with partners on both ends of the supply chain. With upstream raw material suppliers on one end and distribution of varieties of products that require specific product mix settings to address dynamic customer demand on the

downstream end of the LSC. The following are highlights of how this LSC meets the FDSC criteria.

- 1) Product attributes are retail based characterized by dynamic demand.
- 2) Suppliers are required to deal with delivering dynamic volumes of ingredients.
- 3) The manufacturer often faces a pressure to integrate new products to the existing production facilities/equipment to meet high requirements on yield and quality products to be delivered to localized delivery centers.
- 4) The multiple localized distribution centers define the distribution echelon which receives high volume and high mix products.
- 5) The customers in the FDSC are characterized by end users who require on the shelf availability of products.

The next section describes in detail, on how the LSC is characterized to fit the FDSC. Attributes of the supply chains (LSC and FDSC) are first described followed by the explanation of the current performance of the LSC.

4.2 Characterizing the LSC

4.2.1 Characteristics of LSC

In characterizing the LSC, the attributes are described in terms of the product characteristics, the requirements that the manufacturer faces from the downstream of the supply chain, the expectations of the distributor from the manufacturer and what requirements it is intended to comply with and address the internal requirements of product control, and finally, the nature of the customer side of the LSC (see Table 4.1).

Table 4.1: Characteristics of FDSC and LSC

Attributes	Characteristics of FDSC	Characteristics of LSC
Product	A retail product sold in multiple outlets.	Product sold to retail outlets: supermarkets, drugstores, etc. as full case packs, shelf-packs, and individual packs.
	Dynamic product demand - low demand products are taken off the shelf.	High SKU turnover; volatile demand profile.
	There is high level of product mix with high product volume.	It involves high complexity in terms of SKUs, with small amount of product in each SKU.
	New products are introduced every year.	New products are introduced at least once a year. Some products may be introduced twice a year, usually towards the beginning of summer and winter seasons.
Supplier	Two suppliers, each supplying dynamic volume of ingredients.	Multiple continental offshore suppliers, each supplying volume of shades, packages, and other ingredients.
	Long lead times to receive ingredients.	The raw material and packaging sourcing are subject to long lead times.
Manufacturer	Equipment driven manufacturing - dependent upon availability of the equipment.	Dependent on equipment availability and ease in scheduling changes.
	High frequency of setups to produce high product mix.	High frequency of setups to cope with dynamic demand and to add new products.
	High level of pressure to integrate new products.	High level of urgency to launch new products, subject to 8-12 weeks of product evaluation.
		New products must go through weeks of display in retail outlets for customer evaluation before actual production starts.
	High requirement on yield and quality to meet delivery dates.	High requirement on yield and quality to meet delivery dates for in demand products.

Table 4.1 (Continued)

Attributes	Characteristics of FDSC	Characteristics of LSC
Distributor	Multiple localized distribution centers.	Multiple localized distribution centers, each imposing different packaging requirements.
	High volume and mix received on distribution centers.	High product mix and volume that require certain temperature and special care are received in distribution centers.
	High level of product control in distribution.	Picking up of products that did not sell before expiration dates or by inventory turnover season of retails.
Customer	On the shelf availability of products.	Availability of in-demand products for impulse purchasing.

Table 4.1 shows a summary of characteristics for comparing LSC and FDSC.

Supply of ingredients

Global supply chain issues are viewed as part of the business characteristics of LSC, which involves high complexity in terms of numbers of stock-keeping units (SKU), offshore suppliers, SKU turnover, several transactions, and high logistics cost because it requires a responsive replenishment system. Due to the variety of ingredients and packaging to increase product variety, the raw material, and package sourcing is subject to long lead times, usually offshore.

Manufacturing

Manufacturing requires flexible facilities/resources such as workforce, equipment/machine, and scheduling as well as ease for changeover/setup time. The

nature of the products is a short life cycle with a high variety (range). In addition, the packaging of lipstick products is more expensive than the contents (Rundh, 2009). Therefore, the requirement for the availability of packaging materials both in variety and volume adds to the complexity of delivering high mix and high-volume products. Such a relationship between the sourcing end and the manufacturing echelon deems an opportunity to examine the impact of the application of flexibility, which attests the hypotheses.

Distribution

Distribution for the products is usually an inventory-based strategy (i.e., make-to-stock) so that to make sure products are available to respond to the dynamic demand. Distribution is conveyed to multiple outlets, specifically targeting the packaging needs to meet high product mix and high-volume requirements, each, in turn, requiring special care (e.g., temperature). For example, the distribution outlets to high-end consumers are expected to be different from those used for low-end consumers, which makes the distribution echelon to be impacted by any form of flexibility introduced at the manufacturing echelon.

Customer

On the customer end, the nature of the demand exhibits low predictability, high volatility, high impulsive purchasing (on-shelf availability), short shelf life, and seasonality. Many lipstick products sell in a distinct season and are almost entirely replaced in the next season. For instance, darker full-size lipstick is preferred in fall and spring. Seasonality, as it is described later in the current performance of the LSC, is a

challenge at the retail end as well as for the entire chain, warranting the need for flexibility at the manufacturing echelon.

Moreover, with the above characteristics, lipstick as a product is categorized as a fashion product, which makes it the right fit, meeting the criteria for FDSC. In their study on the supply chain of fashion-oriented products, Christopher et al. (2004, p. 368) identified three critical lead times: “time-to-market, time-to-serve, time-to-react”. In the context of FDSC, these critical lead times would resemble the time the manufacturer takes to introduce new products – frequency of new product introduction, hence the new product flexibility; how long the product stays on the shelf before it obsolete, hence this refers to shelf life, and the time to react would be the time to meet delivery dates, hence delivery flexibility. Likewise, conventional market forecasting will not work for fashion-oriented products as accurately as it would for other products. Therefore, characterizing LSC to fit the FDSC enables to study the dynamic – impulsive purchasing of lipstick products.

4.2.2 LSC Fits to FDSC

Addressing the demand characteristics necessitates a flexibility paradigm embraced by the total supply chain. Such a paradigm is a natural fit for an FDSC since it meets the criteria defining it. Flexibility is suitable for a business environment characterized by less predictability where demand is volatile, and a variety of the product is high (Lee, 2002). However, this approach seems to contradict an industry report that indicates “lipstick products are at the maturity phase of the product life cycle”; hence, a hybrid type of

supply chain is more applicable instead of the agile supply chain (Vonderembse, et al. 2006; Huang, 2013).

Perhaps even more challenging is the retail end; on-shelf availability of such diverse products serves as a stimulus for customers. *This forces the supply chain to possess extreme flexibility in manufacturing*, conditions for sensing of demand at the retail, resourcefulness of logistics, and information sharing across the entire chain. The common practice to tackle fluctuations in demand is to manufacture as much as possible and hold inventory of finished products. In continuation characterizing the LSC, once it is justified that the LSC fits FDSC, next is to evaluate the current performance of the LSC based on its existing practices (e.g. lead time to deliver ingredients to the manufacturer, manufacturing processes deeming for flexibility, challenges at the distribution, etc.) and how these can be alleviated with flexibility. This is presented in the next section on the current performance of the LSC.

4.3 Current Performance of the LSC

The supply chain structure of the case study is represented by the flow diagram shown in Figure 4.1. The figure contains some of the supply chain performance indicators such as lead time, amount of inventory and its corresponding dollar value at a specific block from supply of raw materials/ingredients to all the way to the distribution of products at the customer end. To build on the justification described above, that LSC fits FDSC, the current performance of the LSC is presented below, broken-down by echelons.

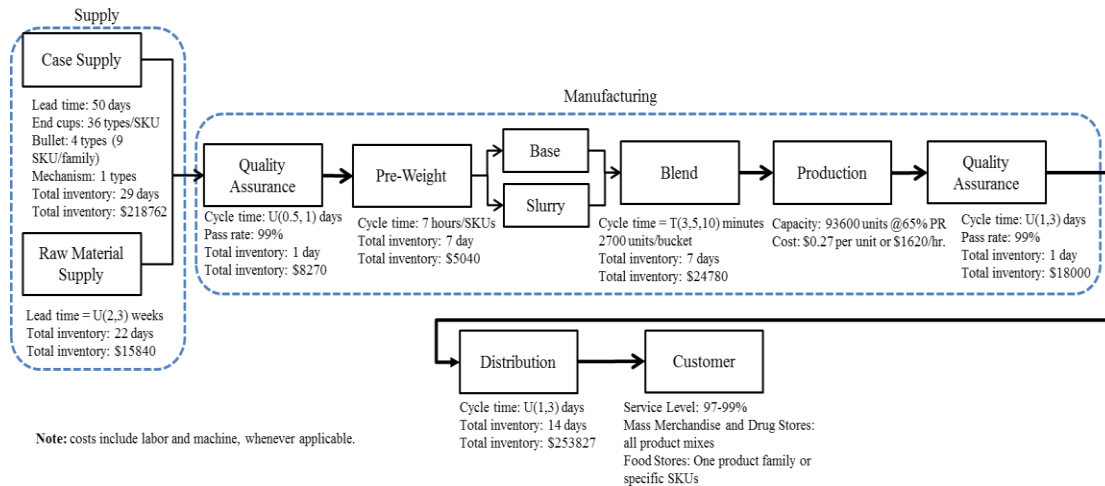


Figure 4.1: Structure of LSC

Supplier

The major raw materials include waxes and oils (base supplies), fragrance (additive), and pigments (shade or color). The geographic location of the supplier of ingredients, packaging, and shades to the manufacturing plant has an imminent impact. That is, an impact on logistics – the time it takes to receive ingredients, the frequency of arrivals or arrival cycles of ingredients, the number of materials received (inventory of ingredients), etc. This means some of the factors that affect supply chain performance (TH and Cost) because of external vulnerability include the geographic locations and physical distance between the supplier and the manufacturer, political situations, inter-country connections, modes of transportation, other technical infrastructures used, as well as unanticipated occurrences (Prater et al., 2001). *These uncertainties drive the need to make sure that there is ample flexibility somewhere in other echelons to compensate for the effect of lead time variability of supplies.*

Figure H.1 (Appendix H) depicts supplier lead time variability. This lead time variability of suppliers in the LSC is another indicator to utilize delivery flexibility at the manufacturing echelon to compensate for any variations in the delivery of ingredients emanating from the supplier. LSC is subject to two main uncertainties: on the external supply and demand fluctuations, which can contribute to diminishing its TH performance or result in excessive cost unless appropriate flexibility is introduced. Moreover, the numbers of suppliers in the LSC are considerably limited and most competitors use the same. This can make it evident for the supplier to pose a dominant position when negotiating for the price of ingredients, so unviable flexibility at the manufacture could result in additional transportation and inventory costs at the inbounding to the manufacturing. This is again having relation to lead time variability one way or the other.

In addition to lead time variability, other performance indicators or metrics related to the supplier are the amounts of inventory of ingredients and its corresponding dollar value. For example, the lead time to receive an ingredient by the manufacturer can range from 2 – 3 weeks and the total inventory is on average for 22 days and its inventory cost including transportation is about \$15,840 on average. *In view of the manufacturer, the above performance indicators are critical to determining which flexibility among VMDI to adjust in order to enhance TH at the manufacturing echelon and minimize cost.* More specifically, it is in the interest of this study to investigate what impact it may create on the supplier if one or more of the VMDI are adjusted at the manufacturing.

Schedule of production and lead time for receipt of ingredients at the manufacturing are the variables, which are controlled at the manufacturing echelon as discussed in section 3.3, corresponding to delivery flexibility. Following along the flow of the supply chain structure presented in Figure 4.1, the current performance of the manufacturing echelon is discussed next.

Manufacturer

The manufacturer in the LSC produces several product categories, which for the interest of this research are categorized into two major types – steady-state and transition products. Products families such as lipstick, lip gloss, lip stains, lip balm, etc., which are produced to serve for both cosmetic and therapeutic demands fall within these two major types. What makes the manufacturing process so complex is that each of these products requires flexibility so that both the steady-state and transition types are produced using available manufacturing facilities (production lines). Another challenge is that the products in LSC may also be included under the cosmetics supply chain (CSC) produced along the lines of makeup items. This implies that the performance of manufacturers in the LCS also impacts CSC and in general the fashion industry, as described above in characterizing the LSC. Therefore, the manufacturing echelon mimicked in Figure 4.1 should be viewed as a simplistic representation of complex manufacturing processes, worth of detailed discussion to further highlight the current performance in view of flexibility. Figure 4.3 is used to illustrate details of the stages.

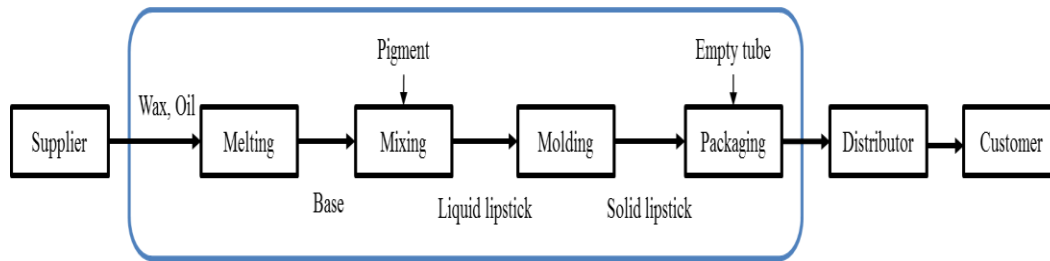


Figure 4.2: LSC's production process

The manufacturing processes are simplified into five major stages. However, depending on the available facilities or production lines, some of the processes/stages may be combined or not available (Baki and Alexander, 2015; Barone et al., 2006).

- 1) Receiving and inspection (quality assurance) of raw materials/ingredients
- 2) Pre-weight
- 3) Blending – combining base to a slurry
- 4) Production – molding, labeling, and packaging
- 5) Outgoing inspection (quality assurance) of finished products

What is so important here is not the number of stages or processes, combinations of operations, etc., it is rather what is involved in each of these processes to affect the current performance of the LSC in general and the manufacturer specifically. Therefore, it is essential to briefly describe each of the above major stages as follows.

Receiving inspection. All base ingredients and additives or special packaging requirements must be inspected. Due to the nature of the complexity of the chemical process (see LSC characteristics), it becomes difficult to rework processed ingredients

and it would result in increased CT or adding delays to process queues, so the quality assurance in the receiving is critical process in manufacturing. Most importantly, if this process is left to allow mediocre materials unidentified and completely processed, it poses health concerns to consumers. From a performance point of view, the current performance shows this process is expected to run at $\frac{1}{2}$ - 1 day CT for a minimal of 36 SKUs and be able to turn 1-day inventory worth of about \$8270, which creates a direct impact on the manufacturing TH and cost of manufacturing as well, as at the system level for these performance indicators.

Pre-weight. Past the receiving inspection, materials are set to be buffered at the Pre-Weight area awaiting to move to the next process for blending proportionally. This stage or process serves not more than a temporary inventory before ingredients are proportionally mixed to create a base. A base is a commonly used mix for all products. What makes a specific product or product mixes is the pigments and other additives going through as slurries.

Blending. This process is an important stage in terms of increasing or decreasing any anticipated product mix. The extent of changes and time introduced to setup time at this stage is assumed to differentiate whether the level of mix flexibility is low or high. The mixture of waxes and oils together, may make-up about 50% of the product by weight. The remaining amount is filled with pigments and other additives. But the percentage can greatly vary depending on the product mix.

Final production. At this stage, the molding process followed by the packaging of the product takes place. Requirements for the specification which adds more complexity

to the production process and demanding more flexibility for product variety makes the process much critical for measuring mix flexibility, as an alternative to the blending stage. The final production stage is also used for investigating volume flexibility since it is at this stage where the final TH is evaluated before it reaches the final product inspection stage. Molding is done at specific temperatures to eliminate certain unwanted elements (foreign particles) using fast cooling in automated molds, which are kept cold by refrigeration. The fast cooling is also used to prevent the formation of bubbles or cratering (Baki and Alexander, 2015). The process of molding involves pouring liquid lipstick into molds, placing it into the refrigerator until it's frozen, removing the solid lipstick from the mold, and cleaning the mold (shoved-off). Before packaging the final product into boxes, which varies by customer, an empty tube is pushed down over the solid lipstick to give it the case that matches the color configuration.

Outgoing inspection. Finally, the manufacturing processes end after the final inspection of finished products is done. There is no doubt any production error will have a significant impact on the TH of manufacturing. But instead of directly dealing with the percentage error or the amount of rework of products which is set at less than 99% acceptance rate of quality, the schedule of quality assurance stage is used to deal with delivery flexibility.

In relation to the manufacturing processes discussed above, the LSC's manufacturing echelon faces challenges that can negatively impact the current performance for yield and quality, hence affect delivery dates and costs. Some examples of frequently identified issues in the final products are sweating, bleeding,

blooming, laddering, and cratering (Barone et al., 2006). Although these issues seem to be inspection problems, they are also essential indicators of the need for flexibility in the manufacturing. For example, sweating, which caused by high oil content or inferior oil binding leads to questioning the receiving inspection of ingredients at the manufacturing but also it requires inherent flexibility to compensate for any lead time variability until replacement ingredients are received from the supplier. Similarly, laddering happens when the product does not look smooth or homogeneous. It is most noticeable in softer formulated products. Another phenomenon is cratering, which is resulted when lipstick develops dimples, and mushy failure: caused due to granularity of the carnauba wax. Laddering and cratering are problems of molding, which indicates the need for volume flexibility in molding or at the final production stage to compensate for any of these issues.

The issues mentioned above might seem minor and ones that can easily be addressed on the production floor with an appropriate flexibility dimension. However, if ignored the issues could cause multifaceted problems if the product reaches the distributor and then the end-users. *This emphasizes the importance of investigating the dimensions and levels of flexibility needed at the manufacturing echelon to proactively mitigate the issues at the manufacturing and their negative impact on the subsequent echelons or on those upstream the manufacturing.*

Distributor and Customer

Reacting to dynamic demand and connecting this to a reliable effort needs a great deal of flexibility all along within the LSC, but most importantly at the inbound and

outbound of the manufacturing echelon. Putting it in a different perspective whether flexibility is effectively implemented or not at the manufacturing will have an impact on the inbound logistics from the supplier (transportation cost and amount of inventory carried) and outbound to the distributor. The challenge at the retail end as well as for the entire supply chain comes from the nature of many of the products in the LSC selling in a distinct season and is almost entirely replaced in the next season. For instance, darker full-size lipstick is preferred in fall and spring. However, these are usually replaced by lighter color lip balm or colored chapstick during summer seasons of the U.S. Figures H.2 and H.3 (Appendix H) show examples of the seasonality of demand for the years 2013 – 2014 and 2014 – 2015, respectively. These figures are based on individual SKUs and reflect how the performance capacity, and thus TH, at the production floor (the manufacturing echelon) is affected.

The current performance of the case company in terms of its practice in innovation flexibility shows that it is dependent upon the effectiveness of sensing the dynamic demand. The schedule is to introduce new products about one to two times a year, towards the beginning of a new year and at the beginning of spring seasons. *But there exists no systematic approach at the manufacturing to investigate how the innovation flexibility impacts the overall performance of TH and cost, and its effect on other dimensions of flexibility.*

Besides to seasonality, the other considerations that can affect the current performance of the LSC are the final touches to the product in terms of packaging and frequently noticed quality issues (briefly described above along the manufacturing

processes). Even for products prepared from the same ingredients, some of them are expected to be delivered at various packaging shapes and sizes. Such a packaging requirement adds considerable variation to the overall product mix held postponing packaging. A combination of having a high product mix to be held which results in tied capital and product availability is the balance needed. But the current performance of the LSC lacks this balance without viable flexibility. Also, unlike other supply chain characteristics, which may not have a direct effect on consumer's health, LSC involves products that can have a direct impact on a consumer's health.

Looking at the LSC current performance across the sector in the U.S., some of the manufacturers tend to either shift their manufacturing operations overseas (Fernandez, 2018) or improve their manufacturing practices but there is lack of introducing flexibility, with the latter aligning with the interest of this study. It was underscored that one of the challenges arise from the dynamic demand from international customers and the toughening competition at local markets against importers of products. From customers at high-end consumer outlets, the other challenge is demanding for the frequent introduction of new products. *This is an alert to the manufacturer to continuously possess or strive for innovation flexibility.* The current performance of the case company in terms of its practice in innovation flexibility shows that it is dependent upon the effectiveness of sensing the dynamic demand. The schedule is to introduce new products one to two times a year, towards the beginning of a new year and at the beginning of spring seasons. But there exists no systematic approach at the manufacturing to investigate how the innovation flexibility impacts the

overall performance of TH and cost, and its effect on other dimensions of flexibility. According to Fernandez (2018), China, Canada, and Italy combined, supply about 70% of industry imports to the U.S., mainly to high-end customers while the low-end products are usually emanated from China and Mexico.

To summarize the current performance of the LSC of the case company and the LSC, in general, implies that inventory-based flexibility is used to respond to uncertainties in dynamic demand. Although accumulating inventory of ingredients, work in processes, and finished products can sometimes provide a short-term significance to the dynamic nature of the LSC environment, this approach comes with a cost of waste in production and tied-up capital over a longer time period. Excess capacity, inventory buffers, and lead time buffers can be used to ensure flexibility requirements, especially for volume and product mix (Pagell et al., 2000; Newman et al., 1993).

4.4 Design of Experiments

4.4.1 Selection of Design

The experimental design approach as discussed in Chapter 3 is BBD, selected due to its suitability to achieving the experimental goals of this research. More specifically, BBD is used to set up where experimental boundaries should be, and to avoid treatment combinations (runs) which are extreme. This means if there are extreme cases where the FDSC behaves, the optimum value of the response variables (TH and Cost) is expected to be obtained centered within the high and low range values, instead of providing misleading results emanating from extreme cases. In other words, misleading

results from outliers that may come, for instance, from the effect of seasonality will be easier to detect when using BBD. Table A.8 shows the BBD developed based on estimated responses from empirical data and from the current performance of the LSC as described in section 4.3.

4.4.2 Design Setup

The selected BBD provides the basis for experimentation and initial experimental results can be obtained from running the Table A.9. But it is not a standalone methods as the hub of this research looks for the DOE – simulation integrated phase for data collection and further analysis. It is also important to validate the metrics mapped using QFD, as discussed in section 3.3. Therefore, macros were developed where the expressions (formulations) are laid out as shown in Figure H.6. These expressions are place holders for conducting the experimentations in simulation. Figure H.7 illustrates a partial view of the scenario's settings, which are run based on the inputs from the expressions in Figure H.6. Next, the simulation strategy is presented which builds on the design setup.

4.5 Simulation

4.5.1 Simulation Modeling Strategy

Before going through the details of the strategy followed to build the simulation model, it is important to reiterate why a DES is preferred. Testing the impact of dimensions of flexibility by physically changing anyone or all of the metrics (see Figures 3.2 and 3.3) on the shop floor at the manufacturing in an FDSC requires extensive investment (e.g.

purchase of equipment, materials, etc.) and dedicated personnel and time for testing scenarios physically. For such a complex process, simulation provides a quick and effective approach to illustrate alternative decision-making options, to enhance TH and reduce cost. The simulation model was developed in a DES platform using ProModel software, which is selected because of its relative ease with which the complex logic (coding) in the manufacturing flexibility can be simulated as well as its availability with an add-in SimRunner optimization tool.

Based on its relevance as discussed in section 4.1, the case company was first approached for data collection needed for developing a simulation base model, and to verify and validate the developed simulation model using performance indicators. The performance indicators were discussed in detail, categorizing them in two key types – leading and lagging indicators in section 3.3. Along the logic developed using the process flow diagram, given in Figure 4.1, the raw data provided in Appendix A is used to develop simulation models to generate additional data and to conduct further experimental analyses to test the methodology described in Chapter 3.

The simulation modeling strategy consists of *three phases*, namely simulation of the base model, scenario analysis based on flexibility dimensions, and optimization model to minimize cost and maximize TH. The strategy starts with the creation of a base model, taking the information and representation of the supply structure, obtained from an actual case study as described above in section 4.2.3. Next, the output from the simulation runs (e.g. TH, cost, WIP, etc.) must be verified and validated. The assumptions considered in the arrival of raw materials (or ingredients), such as the

arrival quantity, arrival times, arrival cycles, costs of transportations of these ingredients, etc. are some of the information verified. At the manufacturing processes, process times, quantities processed, and quantity of specific types of products (steady-state and transition) shipped to the next echelon (i.e., distribution) are some of the other information verified with the data obtained from the case study versus the output from the simulation model.

Since two categories of products are simulated, it is important to note how the order of processing was carried out. The order of specific product category processing was determined using a *priority index* to reflect the demand dynamics of the products (e.g. see Figure H.5). If both products must be produced at the same time period, such as in one season (say in a summer season, within one production shift), the different proportion of steady-state and transition are created.

The methods for determining simulation replication were discussed in subsection 3.6.1. The confidence interval method with a specified precision is more statistically justifiable and it is applicable in subsequent models (e.g. confidence interval must be provided to estimate the precision for the add-in simulation optimization). The optimization phase will be discussed later. With the confidence interval method, it is assumed that the cumulative mean of simulation output (e.g. TH) is normally distributed. This assumption becomes valid as the numbers of replications are large, which makes sense in terms of the central limit theorem.

One reason why multiple replications are needed is to be able to test the reproducibility of the results or outputs. Otherwise, dependence on a single replication

would result in a biased conclusion or interpretation of the results. 10 replications are used as discussed in Chapter 3, where confidence interval based, on obtaining precise performance outputs instead of rough estimates that can be found from running 3 to 5 replications.

Run length is used to determine when the simulation terminates. The run-length in this study is 365 days. The run-length for steady-state products is different from transition products. The latter requires a longer warm-up time. Figure H.3 illustrates how a steady-state of the simulation run is determined. It shows that only after the end of the seventh period, which accounts for about 5% of the entire simulation run length, the system does not reach a steady-state. Therefore, the warm-up time will be set at 5% of the total time. This result was obtained from an average of five replications. Three to five replications are usually recommended (Murray-Smith, 2015) to get rough estimates of output from running a simulation model. Simulation literature suggests adding a safety factor of 20-30% to the warm-up time, while some literature argues against warm-up time and consider it unnecessary (e.g. see Grassmann, 2008). In this study, 5.5% of the total simulation run time is accounted for warm-up to stay within the safety factor.

4.5.2 Simulation Models Verification and Validation

After the simulation strategy is structured, the simulation model can be run, and results obtained. One of the most important concerns during the process of simulation model building are to consistently ensure that the simulated model represents the actual

system (e.g. productions process, supply chain structure, etc.). The task of confirming the degree to which the simulation model accurately represents the real-world environment, or an actual system and the outputs are acceptable with respect to the real data-generating process is referred to as the *model validation*. Since absolute validity is impractical or difficult to achieve, the attainable option is to establish a high degree of *face validity*.

Depending on the complexity of the simulation model and the data-generated and the actual data obtained from the production floor such as those shown in Appendix A, determining the validity could take multiple steps. In this study, the simulation model validity is described using the following two steps. The first step is to closely examine the model structure that is to match the simulation model layout and the actual process flow chart. What is done in this step is simply a verification of how the input-process-output of the developed simulation model is arranged. For verification of the assumptions in building the simulation model – building the right model was discussed with the executives and experts from the case study firm in multiple conference meetings. These meetings proved that the model was built right with “sufficient accuracy” (Pidd, 1996). For example, entity animations were used to demonstrate and distinguish the production of various products categorized into the two major types. The second step is making a comparison of the output results with the historical data obtained from the case company. *Accurately performing these two steps and without significant discrepancies between the actual and simulated system provides a model with face validity.*

Since the values of variables used in DES are assumed to occur instantaneously in a discrete way at a specific instant of time, simulation models developed using DES are clearly an approximate value, while real physical variables cannot change instantly. Therefore, the validation of outputs of the simulation models is discussed in the following section.

4.5.3 Simulation Output Validation

To make a comparison of daily demand versus TH from the simulation model, the simulation run is configured to daily output and TH, CT, etc. are generated daily. The simulation model is set to run for 365 days, to capture seasonality. Relative squared error (RSE) is used as a metric to make a comparison between actual TH of products obtained from the case company and the TH obtained from the simulation model at time period, t .

$$RSE = \frac{\sum (TH_t - \widehat{TH}_t)^2}{\sum (TH_t^2)} \quad (4.1)$$

Where

TH_t : Actual TH of products at time period, t

$\widehat{TH}_t$: TH of products obtained from simulation at time period, t

RSE of about 6.38% indicates that the simulation model represents the actual system output (e.g. see Table A.7 and other datasets in Appendix A). This result reinforces the validation of the simulation model. the role of face validity was also discussed in subsection 4.5.3.

Moreover, production reliability (PR), change over time, supplier lead time, and change in batch size were used as metrics to validate the impact of VMDI on TH and cost. Uniform distribution is used in most cases wherever distribution is deemed necessary (e.g. ingredients arrival time and frequency, process times, etc.) to add some variation depending on the type of product. The results from these initial scenarios were compared with actual data from a case study. Information and data used to develop and validate the baseline simulation model is available in Appendix A. Moreover, the results shown in Table H.1 were sent to the experts in the case firm and the feedback received added further assurance to the validation process. The not significant change (NSC) data included in the table indicates that the flexibility dimension or the associated metrics used did not result in a substantive effect on TH. Cost as an objective value is not included in this table because most of the costs provided here represent total inventory cost. But the cost function will be included in subsequent analysis.

4.6 Hypothesis and Regression Analysis

Based on the hypotheses presented in section 3.1, testing the significance of the performance measures is stated as follows. The null hypothesis (H_0) is that all the TH means are equal. Then, the alternative hypothesis (H_1) is that at least two TH means are significantly different. Similarly, for cost, the null hypothesis is that all the means of total costs are equal. The alternative hypothesis for the cost is that at least two total costs computed are significantly different.

Results of the hypothesis test, taking either one of the objective function values (TH and cost), indicated that there is obviously a significant difference in how a single flexibility dimension can impact at an echelon. Since the comparison of sixteen variables, that is the four dimensions of flexibility on each of the four echelons, is not economically feasible to conduct, the significance of implementation of the VMDI at the manufacturing echelon must be measured as described in the previous section, to evaluate its impact to other echelons. An average value is used which means that the effect of volume flexibility at each echelon is computed and an average value is taken. The same applies to other dimensions.

As shown in Table G.1, the F-test value can be compared to the F-critical value. Since the F-value is less than the F-critical, there is a significant difference in the effect the implementation of dimensions of flexibility it creates when at different echelons, at different amounts. Analysis of variance (ANOVA) was performed to identify the most significant dimensions of flexibility among the VMDI, and how their individual and a combination impact of two or more of them have on TH and cost of the supply chain.

An overview of the regression model is presented in step c in the next section. However, it was found appropriate to discuss the details the regression analysis as part of the results and discussion, Chapter 5.

4.7 Summary

In this chapter, the research methodology was tested using an actual case study. The case firm – an LSC, exhibited similar relevance to the characteristics of the FDSC in

terms of products and the requirements in each echelon. First, the current performances of the LSC are studied. Next, the assumptions, models, the conceptual supply chain, and results measuring leading and lagging indicators are validated based on data obtained from a real case study.

The operational performance metrics were also designed to resemble the case study. Such validation processes were suggested by previous studies (e.g. Gupta and Goyal, 1992). Moreover, RSE is introduced for quantitative validation of simulation outputs in comparison with the actual data from the process that was mimicked. The *three-step validation process* that was followed includes:

- a) Model development with high face validity. Initial historical data of demand for various products were obtained from the case firm. Moreover, the production process was observed, and flow charts created, and the supply chain network studied during on-site visits. Also, pilot runs of simulation models and sensitivity analyses were conducted, which examined the nature of the supply chain process, when subject to variations in levels of flexibility.
- b) Validating model metrics and assumptions. The model assumptions were also compared with the performance metrics used and assumptions considered in the case firm. This includes but not limited to the number of echelons in the supply chain, the key processes in the manufacturing echelon, number of products or family of products, etc.
- c) Validating model output. Besides validating operational performance measures using the initial pilot runs and historical data from the case firm with RSE, statistical

analysis was carried out to test the optimality of response regressions. The goal was to maximize supply chain TH and minimize the total supply chain costs. For example, the regression equation of the TH of manufacturing is represented as follows and graphical and quantitative results are provided in the subsequent chapters.

$$\begin{aligned}
 TH_{mfg} = & 60.00 + 4.29 A - 2.29 B + 5.17 C - 4.25 D + 13.67 A * A + 4.79 B * B \\
 & + 7.23 C * C + 3.10 D * D + 1.00 A * B - 3.88 A * C - 4.25 A * D \\
 & - 3.00 B * C + 6.87 B * D + 1.13 C * D
 \end{aligned}$$

After validation of the methodology via a case study, the next step is to study the impact of the variables of interest on the supply chain performance. Although statistical analysis (regression analysis and hypothesis) should be followed by optimization falling along with the phases in the methodology framework (see Figure 3.1), it is discussed in Chapter 5 where the impacts of implementation of flexibility are presented. It was found appropriate to discuss the results of the optimality of performance indicators after thoroughly presenting the impacts of flexibility.

5 Results and Discussion

The results are presented in two separate but complementary analyses.

- Results related to flexibility changes in manufacturing.
- Results related to the impact on the supply chain.

5.1 Impact of Flexibility on Manufacturing TH

In this section, analysis of the results including the effect of each flexibility dimension on TH and cost – that is the effect of each independent variable on the response variables is illustrated. The rationale for emphasis on manufacturing is because it seems to affect the supply chain performance more (Deshmukh, 2006) as indicated by the historical data analysis (see subsection 4.2.2 for the current performance of the LSC) and other sections in Chapter 4. *More importantly, since the centerpiece of this study is to investigate the impact of manufacturing flexibility, on the performance indicators of the manufacturing echelon and on other echelons, especially those downstream the manufacturing echelon, it echoes to emphasize on manufacturing.* Thus, further analysis is provided in the subsequent sections building on the validation phase discussed previously.

The impacts of dimensions of flexibility – volume (A), mix (B), delivery (C), and innovation (D) as shown in Table B.1, depict their effect on manufacturing TH. Note: the A, B, C, and D are taken from the default settings in the experiment setup, while VMDI

is being used throughout other sections as acronym for volume, mix, delivery, and innovation flexibility respectively. After fitting the model which includes the main effects, 2-way interactions, and square, the statistically significant effects are identified when their p-values are less than the significance level, α , of 0.05. The following effects are significant.

- 1) Three out of four of the main effects in this model, i.e. the volume, delivery, and innovation are significant. The mix flexibility is not identified as significant in this model. This does not mean that the mix flexibility as a dimension is not important; instead, it implies that this dimension has no statistical significance on affecting the throughput at the manufacturing echelon. Another noteworthy mentioning inference here is the significance of the innovation effect. Apparently, it is statistically significant in this model. But its p-value is close to the significance level. This might need further attention and analysis.
- 2) The quadratic regression model depicts volume and delivery as determinants in the rate of change. This is an important observation, especially for a business environment that can make investment decisions to improve its volume production and pay special attention to its lead time needed to allocate before inputs to the production facility are delivered.
- 3) No interaction effects were found to be significant. Perhaps, one may argue the necessity of tradeoffs among some of the effects. However, this does not appear in this model.

The regression equation of the TH of manufacturing is represented as follows, which was also presented in previously along with summarizing the output validations in Chapter 4. It is revisited here for clarity.

$$\begin{aligned} TH_{mfg} = & 60.00 + 4.29 A - 2.29 B + 5.17 C - 4.25 D + 13.67 A * A + 4.79 B * B \\ & + 7.23 C * C + 3.10 D * D + 1.00 A * B - 3.88 A * C - 4.25 A * D \\ & - 3.00 B * C + 6.87 B * D + 1.13 C * D \end{aligned}$$

Normal plot and Pareto charts, shown in Appendix D, are also used to provide further visualization and analysis of a response surface regression.

Figure 5.1 shows a comparison of TH from the manufacturing (TH_mfg) based on results obtained from a simulation run. The results clearly illustrate that volume flexibility and delivery flexibility are the most significantly affecting factors, especially when dealing with steady state products.

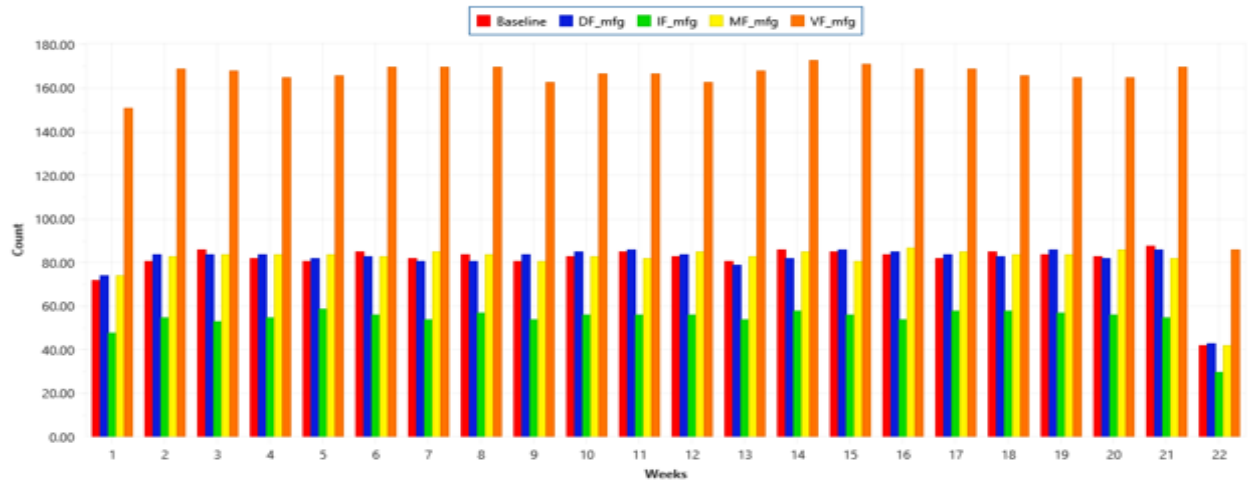


Figure 5.1: Comparison of TH_mfg

Table 5.1: Summary of TH_mfg and CT_mfg

Scenario	TH	CT
Baseline	1796	120.1975
Volume Flexibility	3614	59.74924
Mix Flexibility	1810	119.271
Delivery Flexibility	1809	119.3393
Innovation Flexibility	1196	180.5743

A summary of average results in terms of TH and CT is shown in Table 5.1. CT is in minutes and the unit outputs are in 100s of SKUs.

5.2 Impact of Flexibility on Supply Chain TH and Cost

In this section the impact of flexibility on TH of the supply chain as a system is discussed. Some of the graphs used to show summarized initial results of the effect of dimensions of flexibility on TH of the system are interaction plots, normal plots, and Pareto charts.

An interaction plot is used to show the relationship between two or more factors, and their effects on a response variable. It displays means of the levels of one factor on one axis (e.g. x – axis) and a separate line for each level of another factor. A quick decision can be made through simple observation of the interaction lines. Unless the corresponding lines of the factors are parallel, there exists an interaction. The more nonparallel the lines are the higher the strength of the interaction will be.

As shown in Figure C.1 (Appendix C), regardless of the level of volume, only if mix is set to its low level would result in the highest system TH. That is, the overall

output rate that can be delivered by the supply chain is maximized in terms of volume only if the mix flexibility is minimized. This is an important implication because it ascertains the importance of reduction of setup time or changeover time. As discussed in section 3.3.2, mix flexibility is defined and formulated in relation to changeover time. The results seem to strengthen previous studies (e.g. see Goyal & Netessine, 2011; Salvador et al., 2007). Goyal and Netessine (2011) underlined that even though adding volume flexibility does not negatively affect the system performance, adding mix flexibility to volume flexibility is not always beneficial. On the contrary, Salvador et al. (2007) indicated that the tradeoff existing between these two types of dimensions of flexibility constrains an organization (or its supply chain system) from the perfect implementation of a build-to-order environment. *This is an implication for managers to prioritize volume or mix flexibility or alter specific requirements in processing or to introduce suitable technology or operations.*

The relationship between volume and innovation flexibility is that a high-volume flexibility results at high TH when innovation flexibility is minimized. There is no significant impact on TH of the system when innovation is at its medium level.

Similarly, interpreting the relationship between delivery flexibility and volume flexibility, at high volume and high delivery, the deliverable TH is maximized. Lower delivery and medium volume relationship are where the next higher mean TH of the system is observed.

Moreover, another point worth inferencing for this analysis is when both innovation and mix are minimized. At this point, the TH of the system reaches its

highest level. The regression equation of the TH of the supply chain is represented as follows.

$$TH_{sys} = 54.00 + 3.86 A - 2.06 B + 4.65 C - 3.83 D + 12.30 A*A + 4.31 B*B + 6.51 C*C + 2.79 D*D + 0.90 A*B - 3.49 A*C - 3.82 A*D - 2.70 B*C + 6.19 B*D + 1.01 C*D$$

The normal plot of standardized effects, shown in Figure D.1, is used to aid in separating significant and nonsignificant effects, is usually a self-explanatory graph. As shown in Figure D.1, the variables that have a significant impact of manufacturing TH are volume, delivery, and innovation (as main effects), and delivery and volume when used in their respective squared interactions. These factors are also repeated as significant in the analysis with the cost of manufacturing as a response, shown in Figure D.2. The impact on manufacturing was discussed above in section 5.1.

One alternative to a normal plot of standardized effects is to use a Pareto chart of standardized effects, to identify significant and nonsignificant effects. As shown in Figures D.3 and D.4, with manufacturing TH and System TH as response variables respectively, the Pareto chart uses a reference line to separate significant from nonsignificant effects. *Any of the effects that exceed the reference line, in this case, 2.179, are considered significant effects*, which are volume, delivery, innovation, and squared effects of volume and delivery.

The costs shown in Table 5.2 are a sample display of the impact of flexibility on manufacturing and supply chain costs. This is discussed later in section 5.3.

Table 5.2: Costs associated to VMDI

Scenario	Name	Operation Cost	% Operation Cost	Total Cost	% Total Cost
Delivery	Production Assly	\$ 1,460.16	0.057735367	\$ 1,460.16	0.057735367
Volume	Production Assly	\$ 3,613.19	0.061750692	\$ 3,613.19	0.061750692
Innovation	Production Assly	\$ 14,882.40	0.726895581	\$ 14,882.40	0.726895581
Mix	Production Assly	\$ 17,474.89	0.564159892	\$ 17,474.89	0.564159892
Innovation	Distribution	\$ 31,057.65	1.516937323	\$ 31,057.65	1.516937323
Delivery	Distribution	\$ 36,931.95	1.460305522	\$ 36,931.95	1.460305522
Mix	Distribution	\$ 45,779.66	1.477952434	\$ 45,779.66	1.477952434
Volume	Distribution	\$ 90,852.24	1.552695063	\$ 90,852.24	1.552695063
Innovation	PreWeight	\$ 213,997.68	10.45220985	\$ 213,997.68	10.45220985
Mix	PreWeight	\$ 322,245.36	10.4033816	\$ 322,245.36	10.4033816
Delivery	PreWeight	\$ 323,734.32	12.80059694	\$ 323,734.32	12.80059694
Volume	PreWeight	\$ 326,879.28	5.586476081	\$ 326,879.28	5.586476081
Innovation	Finished QA	\$ 1,787,454.00	87.30395725	\$ 1,787,454.00	87.30395725
Delivery	Finished QA	\$ 2,166,930.00	85.68136217	\$ 2,166,930.00	85.68136217
Mix	Finished QA	\$ 2,712,006.00	87.55450607	\$ 2,712,006.00	87.55450607
Volume	Finished QA	\$ 5,429,916.00	92.79907816	\$ 5,429,916.00	92.79907816

So far, the impact of dimensions of flexibility both at the manufacturing echelon and at the supply chain system is discussed. Next, optimization of the performance indicators – TH and cost, is discussed in the next section. First, using RSM and then using a simulation optimization method.

5.3 Optimality of Performance Indicators

5.3.1 Responses Optimization Type I

Based on the results obtained in sections 5.1 and 5.2, further analysis was conducted to study the impact of dimensions of flexibility, on the optimality of the system output. That is, the factors determined to be effective to enhance manufacturing flexibility – TH at that echelon, are further investigated to predict TH for the system optimality.

In this section, a response optimizer is used to identify the combination of input variables settings used to evaluate the optimality of one or more multiple responses. This is a continuation of the analysis of the impact of dimensions of flexibility with special emphasis given to the manufacturing echelon, on the cost of manufacturing, the total cost of the supply chain, TH of the manufacturing, and TH of the supply chain.

The optimization plot or optimality design profile, shown in appendix E, shows the minimum costs possible and maximum TH values, both at the echelon level as well as the supply chain (see Table E.1 – E.5). *The multiple response prediction plots (see Table E.4), shows 95% confidence interval and 95% prediction interval the response variables. As shown in Table E.5, optimal responses are obtained when the volume is set at 65%; the mix is decreased by 86%; delivery is increased by 15%, and innovation*

reduced by 23%. The above response variables are predicted at the squared error of 8.32, 3.33, and 3.70, which implies that the fitted model can be used as a reasonable indicator for further sensitivity analysis. When the optimality design profile is lively displayed, it allows one to visualize and perform sensitivity analysis.

5.3.2 Response Optimization Type II

This subsection illustrates an alternative approach to the optimization technique discussed above. It is considered an advanced level to the options provided in the previous section. However, as shown in the subsequent discussions, it will also open an opportunity for future research to build on observed drawbacks or to take better benefits of the benefits achieved.

The Steps of simulation optimization are the following. These steps have been explained in Chapter 3, but they are revisited here with more details and aligned with results.

- 1) An initial set of parameter values is chosen, and experiments are run with these values. This is where parameters are created as macros in the simulation model.
- 2) The results are obtained from the simulation runs and then optimization module chooses another parameter set to try.
- 3) The new values are set, and the next experiment set is run.
- 4) Steps 2 and 3 are repeated until either the algorithm is stopped manually or based on defined finishing conditions (e.g. simulation run length).

SimRunner provides three optimization profile options, namely cautious, moderate, and aggressive respectively, ranging from a profile that uses a high combination of elements to one that tries less combination of an element. *For most models, moderate seems to work well and this type of profile is used in this study just for simplicity and to run a reasonable combination of elements.* The convergence percentage, which refers to the accuracy of the number of runs is kept at its default setting (0.01). The number of replications is set to 2 to make sure some variability is added to the experiment. Warmup time and run-time are kept at default settings, which was the same as the actual simulation model.

All these model settings are validated by the first stage of the simulation optimization using SimRunner – the analysis phase. Figure F.1 shows two figures illustrating this stage. The one on the left was used when only one variable (cost) was the response variable. The other, on the right, is where both TH and cost are the response variable – hence a multi-objective simulation optimization model is created. The second stage is the optimization.

The wave-like graphs shown in Figure F.2 represents the number of experiments run and indicates which experiment results in higher attempted values and which else results in the lowest values. *The figure shows that experiment #12 provides the minimum value of the objective function, with high volume flexibility to absorb disruptions from the supplier echelon (only one of the input materials that is set at a high interarrival time in the actual simulation model's scenarios), high delivery at distribution*

echelon, and low level mix at the manufacturing echelon. The corresponding inputs in the sample data of experimental runs in Table F.1, these values are in columns 3 – 7.

Further analysis, now with both cost and TH as competing responses, search for optimal solution converged in generation 2 and experiment number 30. Experiment #30 resulted in an optimal value. This is shown in Table F.2. Experiment #29 provides the next optimal value after experiment #30. As shown in the table, the marginal difference among subsequent alternative solutions of the experiments for TH is very small, while the marginal difference in cost gets higher. The implication related to which flexibility dimensions and the impact on the manufacturing echelon, the echelons pre and post the manufacturing, and the supply chain system is not different from the discussion above.

5.4 Summary

In this fifth chapter, the results and discussion were presented. Generally stated, the conceptual research framework is which was validated previously, is reinforced further quantified results and the implications to the FDSC system discussed. Also, two approaches to optimization are tested, and their results compared.

The impacts of VMDI implementation are recapped as follows. Implementation of volume flexibility was found to have a positive impact both to the manufacturing performance, that is, the manufacturing echelon and the supply chain as a system. Thus, its effect on the performance of the echelons pre and post the manufacturing can be affected significantly. Since the volume flexibility is defined as a function of demand,

the echelons downstream the manufacturing echelon are apparently subject to direct influence by whatever is introduced at the manufacturing. On the supplier's end, changes caused by volume flexibility affects the supplier's ability to modify its products (raw materials to the manufacturing echelon) to meet the changes needed by the manufacturer.

Mix flexibility shows no significant positive impact on TH_mfg. This is because manufacturing flexibility exacerbates disruption and add more variation in the manufacturing process. Low performance of TH_mfg in turn results in diminished TH to be delivered to the next echelon downstream.

Although responding quickly to existing or anticipated demands arising from the customer end is important, delivery alone cannot be a winning tool. There must be an inherent capacity at the manufacturing which will enable to address the demand of a variety of products that often come in high volumes (e.g. hundreds of SKUs per product family) required at a customer end. Therefore, volume flexibility and mix flexibility must be predecessors to delivery flexibility. However, innovation flexibility although it may contribute to increasing product mix, hence mix flexibility, it does not come in a speedy manner. Another point that can minimize disruption of ingredients from the supplier side, especially during seasons when fluctuations of demand are observed, is to have a WIP in the form of an in-process inventory at the manufacturing echelon (e.g. in-process inventory in a generic form that is not blended to a specific shade yet).

Innovation flexibility is needed in order to enhance business growth and survival by continuously expanding to new potential customers (Ozer, 1999). Although when

implemented for strategic decisions, over a long term, innovation flexibility may be found to have a positive relationship to TH, in operational decisions, its relationship to TH is negative. This could be due to many reasons. For example, new product development requires initial investment in terms of time (changeover time, process time, delivery time to the next echelon, etc.) so it is correlated to delivery flexibility. Other requirements include production cost per unit which can increase or decrease depending on the ability of the resources on the production floor to make the new product development time short or long. Not only these, since the new products must be developed within the existing process, examining the capability of the process to produce high volume of new products prototypes and to increase the variety of new products is important. The business environment of FDSC usually introduces new product at least 1 to 2 times per year. In other words, innovation flexibility is used to contribute to overall requirements for the mix flexibility; hence there is positive relationship between these dimensions.

To achieve VMDI to its fullest potential, a chase strategy (i.e. chasing the demand and adjust one or a combination of the VMDI) is suitable production method. The characteristics of FDSC exhibit fluctuation in demand, short product life cycle, seasonality, etc. to reiterate a few of them makes chasing a preferred strategy. By chasing the demand and producing accordingly can help to realize volume and mix requirements. Similarly, it supports to respond quickly, hence utilizing and applying delivery flexibility thoroughly. Innovation flexibility, with the prerequisites needed to realize it comes as a last priority in VMDI application.

Although TH is used as one of the lagging indicators – viewed to respond to the amount of demand by increasing the yield at the manufacturing, which in turn contributes to reducing the average production cost per unit, the total cost (including transportation, inventory, etc.) must be included as additional indicator for FDSC. In relation to VMDI, the total cost can be viewed as follows. Reducing a setup time increases mix flexibility, and then reducing setup cost as well as increasing production yield (note: production runs are assumed to be directly proportional to yield, as the quality is not a major concern). Quality is not a major concern means, for this study, it is not one of the factors considered for analysis. Finally, the optimization models indicate the need for a tradeoff between TH and cost through the manipulation of one or more of the VMDI.

Following the presentation of results and discussion of the implications of these results in the FDSC, it is important to summarize the entire study. Managerial and technical implications are discussed. Every study has limitations, but those limitations can serve as opportunities when supported by a clear direction for further research. Hence, the next chapter provides key implications, limitations, and ideas for future research.

6 Conclusions and Future Research

6.1 Research Overview

To enhance a supply chain's performance, the key focus has been on efficiency. The literature has suggested agility as a means of enhancing a supply chain's performance. Flexibility is one primary measure of agility. The motivation is to embed efficiency and flexibility to enhance supply chain effectiveness.

This study provides a methodology for decision-makers in the supply chain of high-volume and high-variety industries where the issues pertaining to the measures and metrics of flexibility are addressed. The central questions addressed are: wherein the supply chain and at what level can flexibility be applied? What impact does implementation of manufacturing flexibility cause to other echelons, upstream and downstream the manufacturing? Which dimension of flexibility is more appropriate and what is its impact on other flexibility dimensions as well as on maximizing supply chain TH while minimizing supply chain cost?

The major contributions made by this study are discussed in the following sections. The contributions can be viewed in terms of theoretical, methodological, or technical, and practical implications.

6.2 Contributions

Results of this study are aligned to support a theory that provides the dimensions and major metrics required to define measures of flexibility, and then the performance of agility of supply chain for an FDSC. The dimensions of flexibility obtained from a comprehensive review of literature were barely defined in the context of FDSC.

The key findings from the case study indicated that the current performance indicators deemed the need for implementation of manufacturing flexibility based on the nature of the product and the LSC characteristics to benefit from the theoretical foundation that the FDSC basis. To reduce complexity and for ease of feasibly implementing the theoretical/conceptual framework, only four echelons (supplier, manufacturer, distributor, and retail/customer) are considered. Products were categorized into the transition and steady-state products.

In the context of operational excellence, this research provides integration of flexibility to efficiency to define operational effectiveness. This research provides a systematic approach for analysis of dimensions of flexibility in the design of an integral “Lean – Flexibility” system as a strategic alliance to enhance supply chain performance, with emphasis on VMDI, which have a greater impact on lagging performance indicators (TH and cost) of the supply chain.

Another, and perhaps a key contribution is the redefinition of dimensions of flexibility which is supported by mathematical formulations by taking “weight” of the type of product considered (transitional and steady-state). *With this approach, the research contributes to the body of knowledge of supply chain flexibility and delivers managerial*

implications in terms of identifying key metrics for the discrete manufacturing supply chain by integrating flexibility for supply chain performance. Operations managers will be able to distinguish which flexibility dimension and the associated metrics to utilize to enhance supply chain performance.

As mentioned above, the research methodology was validated using a case study in the LSC. Therefore, potential applications resulting from this study include a manufacturing system that operates in a high-volume and high-variety production environment. *Potential applications of the developed Flexible Discrete Supply Chain (FDSC) is for supply chain systems that are considered to fall within the category of discrete manufacturing.*

However, it is rational to assume that any research has a limitation, which would serve as an opportunity for further research. This study is not different. The next section discusses future research direction including the application of the methodology in other settings.

6.3 Limitation and Future Research

As part of the experimentation, especially to explore flexibility at the manufacturing echelon, BBD was used. But BBD lacks the ability to explain if the response surface happens to be at the extreme value. Future studies should consider a different technique to visualize the effect of extreme cases. Other non-response surface designs such as Taguchi OA Design can be utilized for further exploration.

In a similar note, the simulation optimization technique used in this study was based on an evolutionary algorithm. Two problems observed with this technique are slow convergence and lack of generally acceptable termination criteria. This leads to terminate it either by trial and error or to limit the number of generations. In either case, there may be an error in estimating the global optimal. Therefore, another approach would be recommended as a future study.

Another possible limitation lies in the dimensions of flexibility. Some of the dimensions are difficult to quantify, so changing these to categorical factors can be used for future investigation. One example is the innovation flexibility. This dimension would be better addressed using a qualitative approach like a survey as it might also involve unquantifiable company policies.

Moreover, future research is recommended to take this product to the next level of research in terms of mathematical modeling such as multi-objective criterion, expand the validity of the research framework in other similar industries or modify it to fit other industry sectors, adding complexity to the supply chain network or variables of interest (e.g. additional echelons or locations to the existing supply chain structures, external influencing factors, etc.) and adding fuzzy logic (artificial intelligence approach) to qualitative variables.

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Appendices

A. Raw Data from Case Study

Table A.1: Monthly demand overview for SKU #1

Statistic	Cases	Shelf Packs
Mean	98.8	1376.7
Standard Deviation	34.4	329.5

Table A.2: Per unit breakdown of SKU #1 (monthly overview)

Overall Average	9869
Overall Standard Deviation	2561
Case % of Total Volume	71.4%
Case % of Shipments	6.7%

Table A.3: Monthly demand overview for SKU #2

Statistic	Cases	Shelf Packs
Mean	72.5	1146
Standard Deviation	13.3	545.1

Table A.4: Per unit breakdown of SKU #2 (monthly overview)

Overall Average	7512
Overall Standard Deviation	1453
Case % of Total Volume	70.2%
Case % of Shipments	5.9%

Table A.5: Monthly demand overview for SKU #3

Statistic	Cases	Shelf Packs
Mean	35	620.2
Standard Deviation	19.3	161.3

Table A.6: Per unit breakdown of SKU #3 (monthly overview)

Overall Average	3760
Overall Standard Deviation	41.4
Case % of Total Volume	64.1%
Case % of Shipments	5.3%

Table A.7: Experimental design methods

Date	Case pack per month	Shelf pack per month	SKU	CP per shipping-day	SP per shipping-day	CP_units per day	SP_units per day
Jul-14	125	1870	1	7	94	474	187
Jul-14	83	1348	1	4	67	315	135
Jul-14	63	954	1	3	48	239	95
Jul-14	151	1644	1	8	82	572	164
Jul-14	68	1241	1	4	62	258	124
Jul-14	103	1203	1	5	60	390	120
Jul-14	69	957	2	4	44	276	87
Jul-14	57	732	2	3	33	228	67
Jul-14	84	2159	2	5	98	336	196
Jul-14	66	1332	2	4	61	264	121
Jul-14	93	706	2	5	32	372	64
Jul-14	66	990	2	4	45	264	90
Jul-14	56	846	3	4	38	252	77
Jul-14	16	465	3	1	21	72	42
Jul-14	16	549	3	1	25	72	50
Jul-14	36	720	3	2	33	162	65
Jul-14	26	438	3	2	20	117	40
Jul-14	60	703	3	4	32	270	64

Table A.8: Experimental design methods

Method	Number of experiments	Suitability
Randomized complete block design (RCBD)	$N(L_i) = \prod_{i=1}^k L_1$	focus on primary factors using blocking
Latin square	$N(L) = L^2$	focus on primary factors cheaply
Full factorial	$N(L, k) = L^k$	compute main effects and interaction effects; build response surface
Fractional factorial	$N(L, k, p) = L^{k-p}$	estimate main effects and interaction effects
Central composite design (CCD)	$N(k) = 2^k + 2k + 1$	building response surfaces
Box-Behnken design (BBD)	$N(k)$ from table	building quadratic response surfaces
Taguchi	$N(k_{in}, k_{out}, L)$ from table	address the influence of noise factors
Random	Chosen by experimenter	building response surfaces
Optimal design	Chosen by experimenter	building response surfaces

Table A.9: Box-Behnken Design

Std Order	Run Order	Pt Type	Blocks	V	M	D	I	TH_mfg	TH_sys	Cost_sys
24	1	2	1	0	1	0	1	65	58.5	146.25
5	2	2	1	0	0	-1	-1	75	67.5	168.75
3	3	2	1	-1	1	0	0	70	63	157.5
1	4	2	1	-1	-1	0	0	80	72	180
26	5	0	1	0	0	0	0	60	54	135
20	6	2	1	1	0	1	0	85	76.5	191.25
11	7	2	1	-1	0	0	1	72	64.8	162
9	8	2	1	-1	0	0	-1	74	66.6	166.5
12	9	2	1	1	0	0	1	68	61.2	153
7	10	2	1	0	0	-1	1	70.5	63.45	158.625
17	11	2	1	-1	0	-1	0	68	61.2	153
21	12	2	1	0	-1	0	-1	83.5	75.15	187.875
19	13	2	1	-1	0	1	0	82.5	74.25	185.625
25	14	0	1	0	0	0	0	60	54	135
22	15	2	1	0	1	0	-1	64	57.6	144
6	16	2	1	0	0	1	-1	72	64.8	162
14	17	2	1	0	1	-1	0	61	54.9	137.25
10	18	2	1	1	0	0	-1	87	78.3	195.75
23	19	2	1	0	-1	0	1	57	51.3	128.25
27	20	0	1	0	0	0	0	60	54	135
15	21	2	1	0	-1	1	0	86	77.4	193.5
16	22	2	1	0	1	1	0	80	72	180
2	23	2	1	1	-1	0	0	89	80.1	200.25
13	24	2	1	0	-1	-1	0	55	49.5	123.75
18	25	2	1	1	0	-1	0	86	77.4	193.5
8	26	2	1	0	0	1	1	72	64.8	162
4	27	2	1	1	1	0	0	83	74.7	186.75

B. Response Surface Regression – TH of Manufacturing

Table B.1: ANOVA – main and interaction effects

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	14	2255.36	161.097	3.68	0.015
Linear	4	821.12	205.281	4.69	0.016
A	1	221.02	221.021	5.05	0.044
B	1	63.02	63.021	1.44	0.253
C	1	320.33	320.333	7.32	0.019
D	1	216.75	216.750	4.95	0.046
Square	4	1067.80	266.949	6.10	0.006
A*A	1	996.15	996.148	22.76	0.000
B*B	1	122.45	122.454	2.80	0.120
C*C	1	278.72	278.725	6.37	0.027
D*D	1	51.39	51.391	1.17	0.300
2-Way Interaction	6	366.44	61.073	1.40	0.293
A*B	1	4.00	4.000	0.09	0.768
A*C	1	60.06	60.063	1.37	0.264
A*D	1	72.25	72.250	1.65	0.223
B*C	1	36.00	36.000	0.82	0.382
B*D	1	189.06	189.063	4.32	0.060
C*D	1	5.06	5.063	0.12	0.740
Error	12	525.27	43.773		
Lack-of-Fit	10	525.27	52.527	*	*
Pure Error	2	0.00	0.000		
Total	26	2780.63			

Table B.2: ANOVA – model summary

S	R-sq	R-sq(adj)	R-sq(pred)
6.61608	81.11%	59.07%	0.00%

Table B.3: ANOVA – coded coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	60.00	3.82	15.71	0.000	
A	4.29	1.91	2.25	0.044	1.00
B	-2.29	1.91	-1.20	0.253	1.00
C	5.17	1.91	2.71	0.019	1.00
D	-4.25	1.91	-2.23	0.046	1.00
A*A	13.67	2.86	4.77	0.000	1.25
B*B	4.79	2.86	1.67	0.120	1.25
C*C	7.23	2.86	2.52	0.027	1.25
D*D	3.10	2.86	1.08	0.300	1.25
A*B	1.00	3.31	0.30	0.768	1.00
A*C	-3.88	3.31	-1.17	0.264	1.00
A*D	-4.25	3.31	-1.28	0.223	1.00
B*C	-3.00	3.31	-0.91	0.382	1.00
B*D	6.87	3.31	2.08	0.060	1.00
C*D	1.13	3.31	0.34	0.740	1.00

Table B.4: ANOVA – fits and diagnostics of unusual observations

Obs	TH_mfg	Fit	Resid	Std Resid	
10	70.50	59.79	10.71	2.51	R
24	55.00	66.15	-11.15	-2.61	R

C. Response Surface Regression – TH and Cost of System

Table C.1: ANOVA – main and interaction effects in TH_sys

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	14	1826.84	130.489	3.68	0.015
Linear	4	665.11	166.278	4.69	0.016
A	1	179.03	179.027	5.05	0.044
B	1	51.05	51.047	1.44	0.253
C	1	259.47	259.470	7.32	0.019
D	1	175.57	175.568	4.95	0.046
Square	4	864.92	216.229	6.10	0.006
A*A	1	806.88	806.880	22.76	0.000
B*B	1	99.19	99.187	2.80	0.120
C*C	1	225.77	225.767	6.37	0.027
D*D	1	41.63	41.627	1.17	0.300
2-Way Interaction	6	296.81	49.469	1.40	0.293
A*B	1	3.24	3.240	0.09	0.768
A*C	1	48.65	48.651	1.37	0.264
A*D	1	58.52	58.522	1.65	0.223
B*C	1	29.16	29.160	0.82	0.382
B*D	1	153.14	153.141	4.32	0.060
C*D	1	4.10	4.101	0.12	0.740
Error	12	425.47	35.456		
Lack-of-Fit	10	425.47	42.547	*	*
Pure Error	2	0.00	0.000		
Total	26	2252.31			

Table C.2: Model summary

S	R-sq	R-sq(adj)	R-sq(pred)
5.95448	81.11%	59.07%	0.00%

Table C.3: Coded coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	54.00	3.44	15.71	0.000	
A	3.86	1.72	2.25	0.044	1.00
B	-2.06	1.72	-1.20	0.253	1.00
C	4.65	1.72	2.71	0.019	1.00
D	-3.83	1.72	-2.23	0.046	1.00
A*A	12.30	2.58	4.77	0.000	1.25
B*B	4.31	2.58	1.67	0.120	1.25
C*C	6.51	2.58	2.52	0.027	1.25
D*D	2.79	2.58	1.08	0.300	1.25
A*B	0.90	2.98	0.30	0.768	1.00
A*C	-3.49	2.98	-1.17	0.264	1.00
A*D	-3.82	2.98	-1.28	0.223	1.00
B*C	-2.70	2.98	-0.91	0.382	1.00
B*D	6.19	2.98	2.08	0.060	1.00
C*D	1.01	2.98	0.34	0.740	1.00

Table C.4: Fits and diagnostics of unusual observations

Obs	TH_sys	Fit	Resid	Std Resid	
10	63.45	53.81	9.64	2.51	R
24	49.50	59.53	-10.03	-2.61	R

Table C.5: Main and interaction effects in Cost_sys

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	14	11417.8	815.55	3.68	0.015
Linear	4	4156.9	1039.24	4.69	0.016
A	1	1118.9	1118.92	5.05	0.044
B	1	319.0	319.04	1.44	0.253
C	1	1621.7	1621.69	7.32	0.019
D	1	1097.3	1097.30	4.95	0.046
Square	4	5405.7	1351.43	6.10	0.006
A*A	1	5043.0	5043.00	22.76	0.000
B*B	1	619.9	619.92	2.80	0.120
C*C	1	1411.0	1411.04	6.37	0.027
D*D	1	260.2	260.17	1.17	0.300
2-Way Interaction	6	1855.1	309.18	1.40	0.293
A*B	1	20.2	20.25	0.09	0.768
A*C	1	304.1	304.07	1.37	0.264
A*D	1	365.8	365.77	1.65	0.223
B*C	1	182.3	182.25	0.82	0.382
B*D	1	957.1	957.13	4.32	0.060
C*D	1	25.6	25.63	0.12	0.740
Error	12	2659.2	221.60		
Lack-of-Fit	10	2659.2	265.92	*	*
Pure Error	2	0.0	0.00		
Total	26	14076.9			

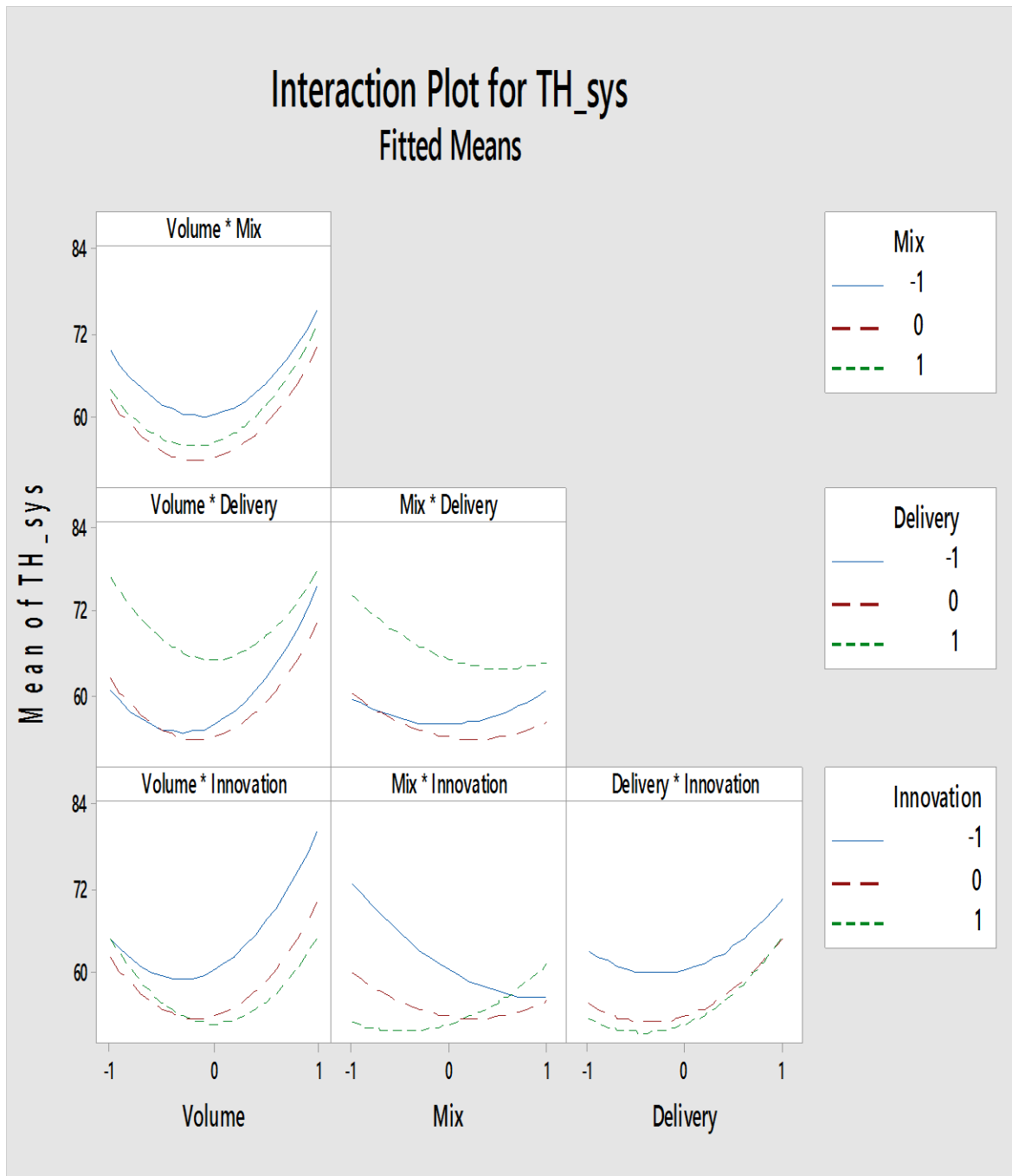


Figure C.1: Interaction plot of TH_sys – fitted mean

D. Normal plot and pareto chart

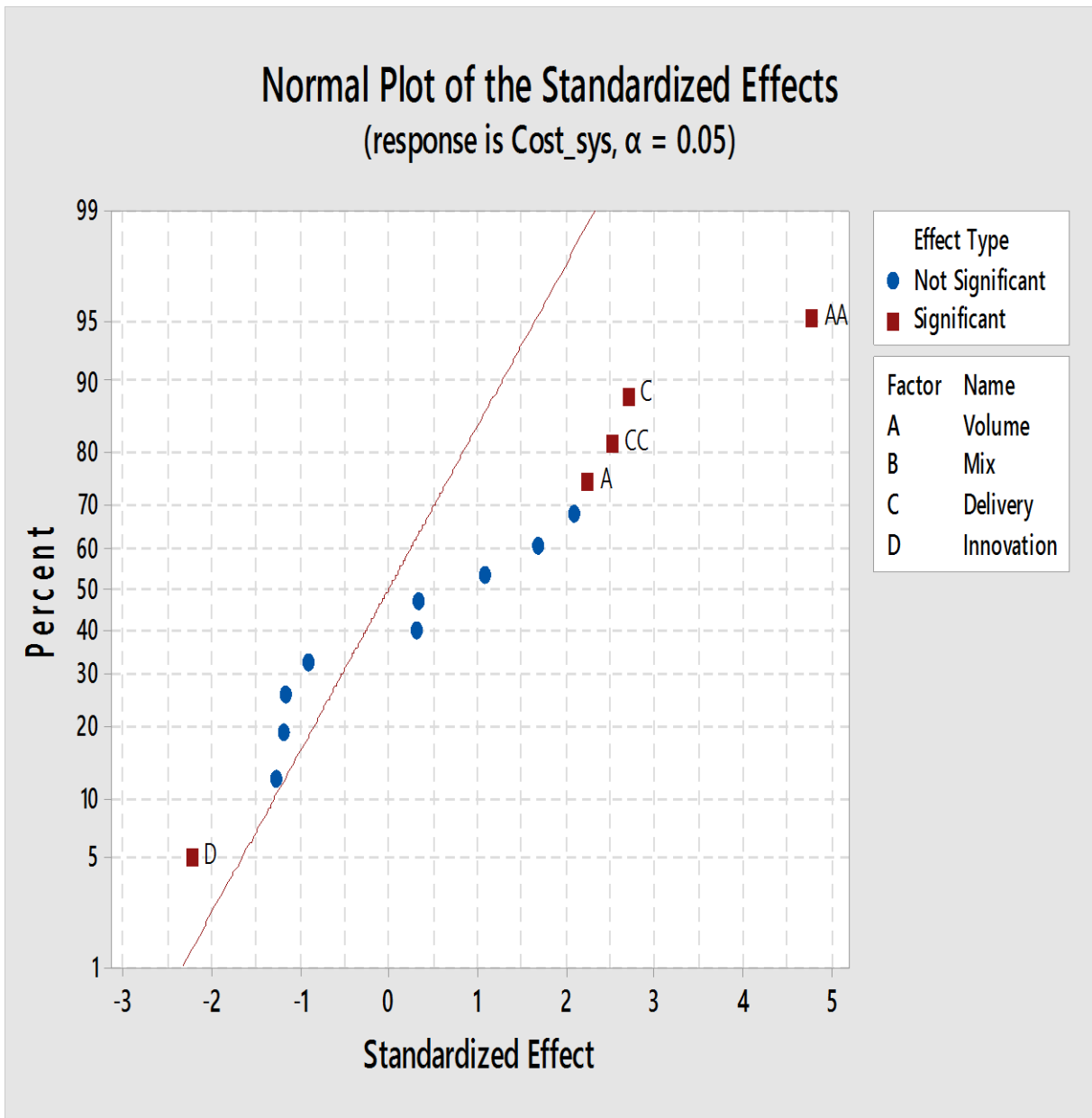


Figure D.1: Normal plot of standardized effects - Cost_sys as response

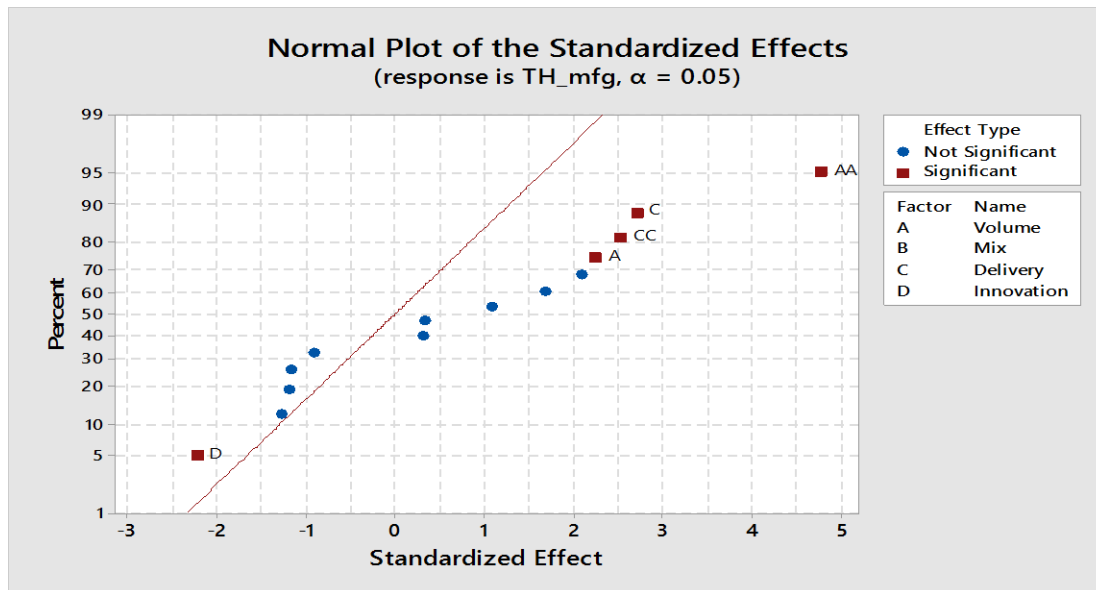


Figure D.2: Normal plot of standardized effects – TH_mfg as response

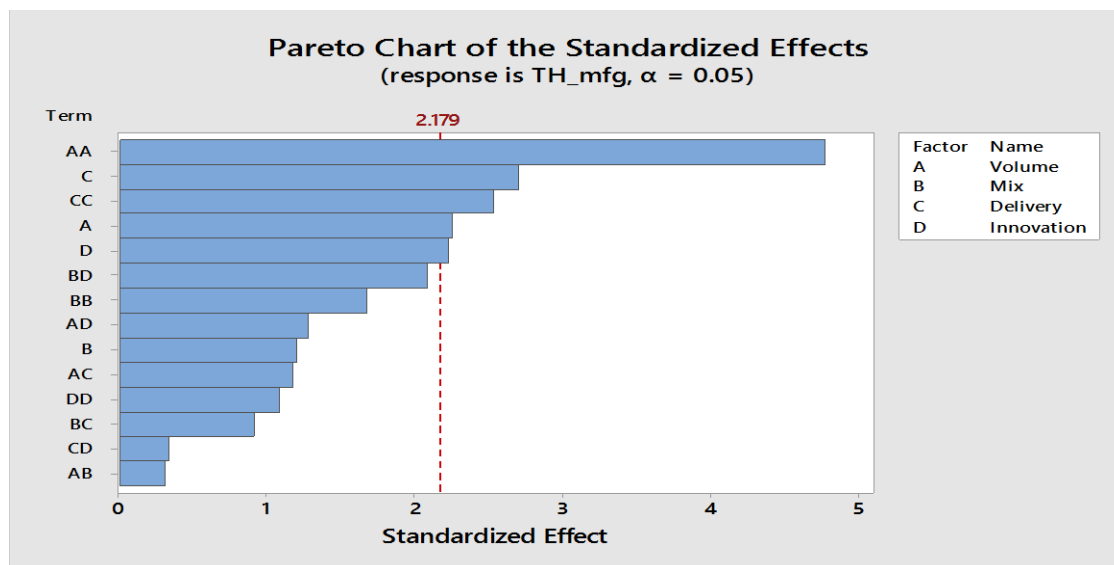


Figure D.3: Pareto chart of standardized effects – TH_mfg

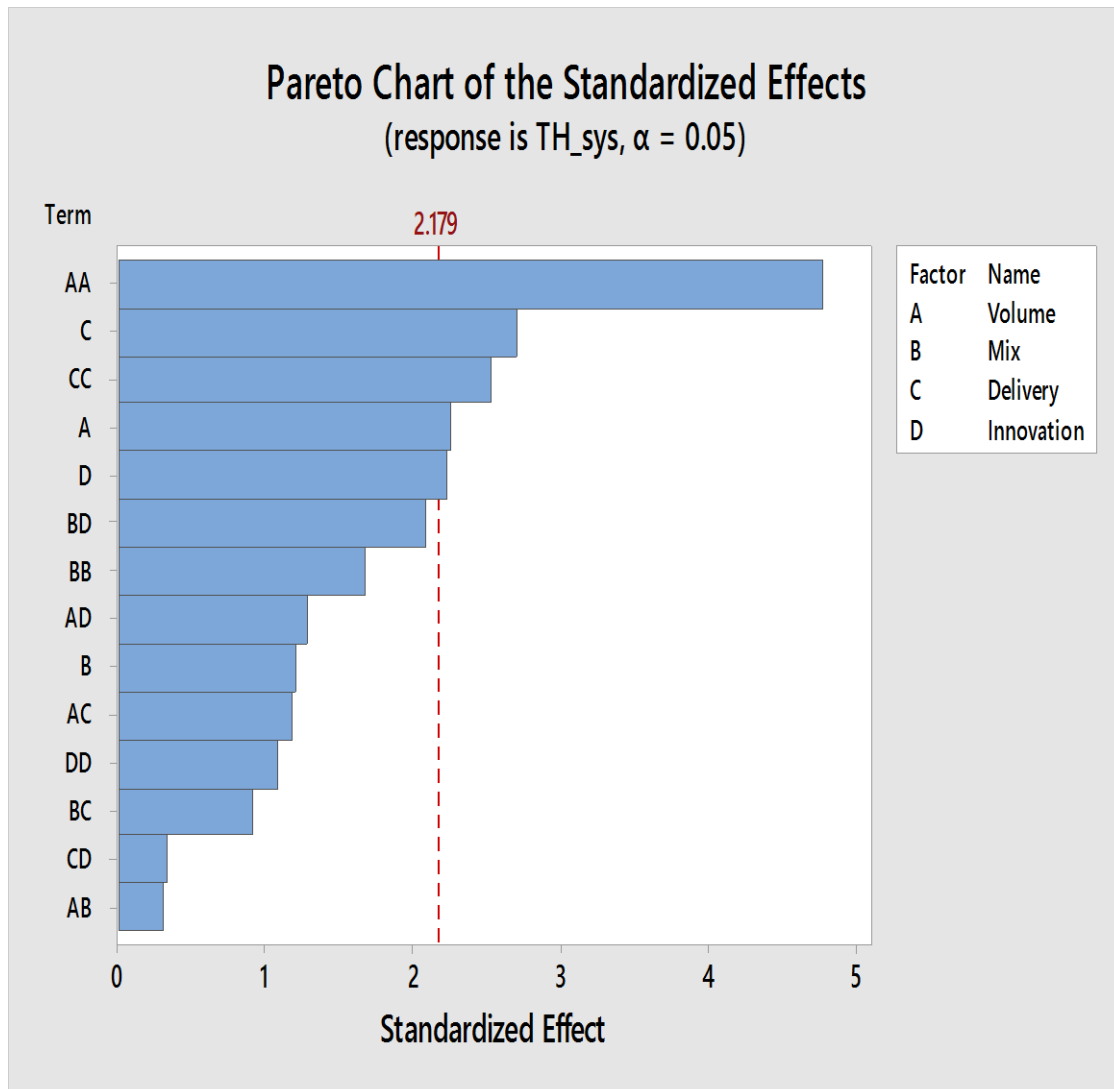


Figure D.4: Pareto chart of standardized effects – TH_sys

E. Response Optimization

Table E.1: Response Optimization: Cost_sys, TH_sys, TH_mfg Parameters

Response	Goal	Lower	Target	Upper	Weight	Importance
Cost_sys	Minimum		123.75	200.25	1	1
TH_sys	Maximum	49.5	80.10		1	1
TH_mfg	Maximum	55.0	89.00		1	1

Table E.2: Variable ranges

Variable	Values
Volume	(-1, 1)
Mix	(-1, 1)
Delivery	(-1, 1)
Innovation	(-1, 1)

Table E.3: Solution

Soluti on	Volum e	Mix	Deliver y	Innovati on	Cost_s ys Fit	TH_s ys Fit	TH_m fg Fit	Composi te Desirabil ity
1	0.6500 23	- 0.8621 81	0.1515 15	- 0.23457 8	174.750	69.90 02	77.66 69	0.529134

Table E.4: Multiple response prediction

Variable				Setting
Volume				0.650023
Mix				-0.862181
Delivery				0.151515
Innovation				-0.234578
Response	Fit	SE Fit	95% CI	95% PI
Cost_sys	174.75	8.32	(156.62, 192.88)	(137.59, 211.91)
TH_sys	69.90	3.33	(62.65, 77.15)	(55.04, 84.76)
TH_mfg	77.67	3.70	(69.61, 85.72)	(61.15, 94.18)

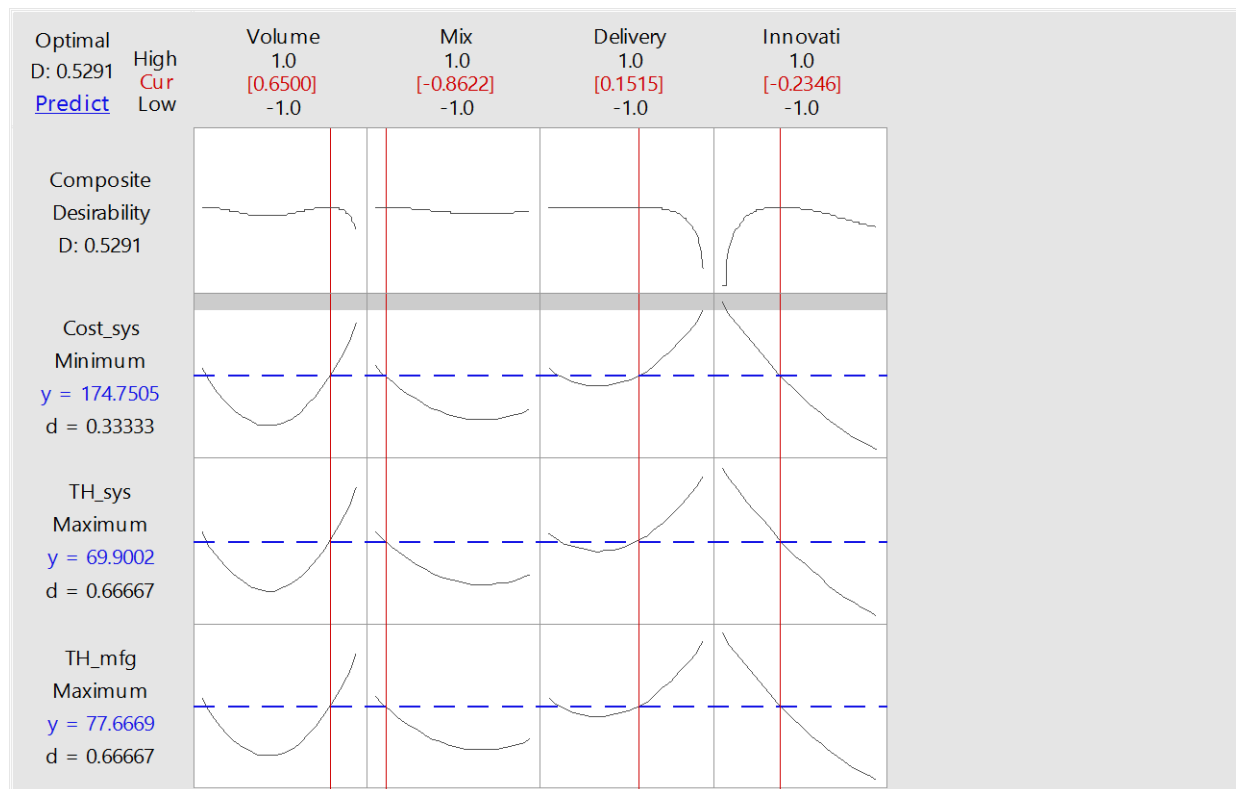


Figure E.1: Optimality design profile

F. Simulation Optimization

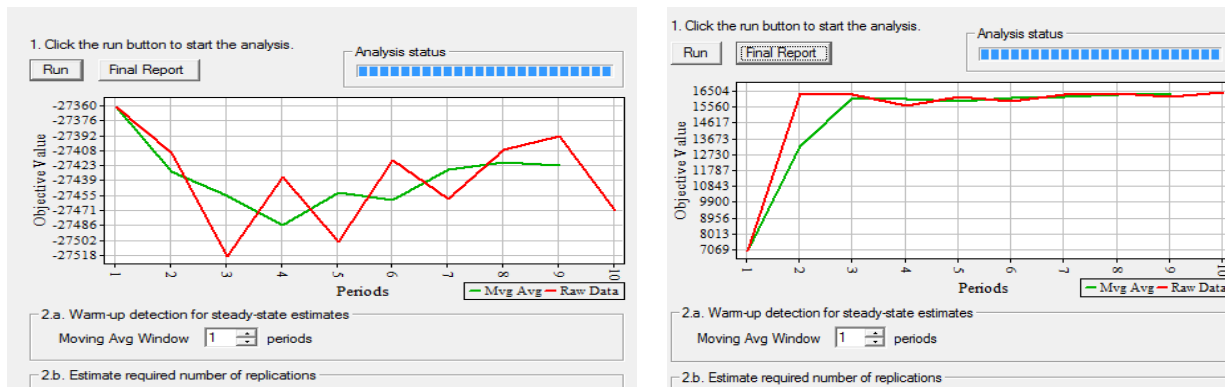


Figure F.1: Optimality first stage

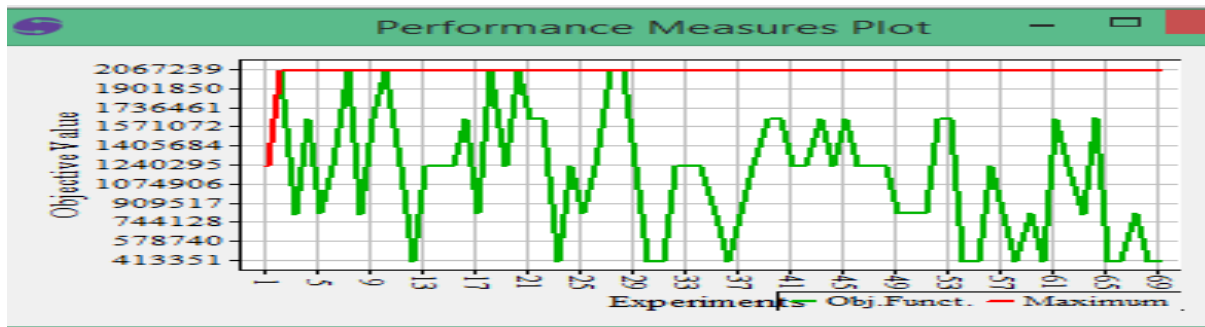


Figure F.2: Optimality second stage #1

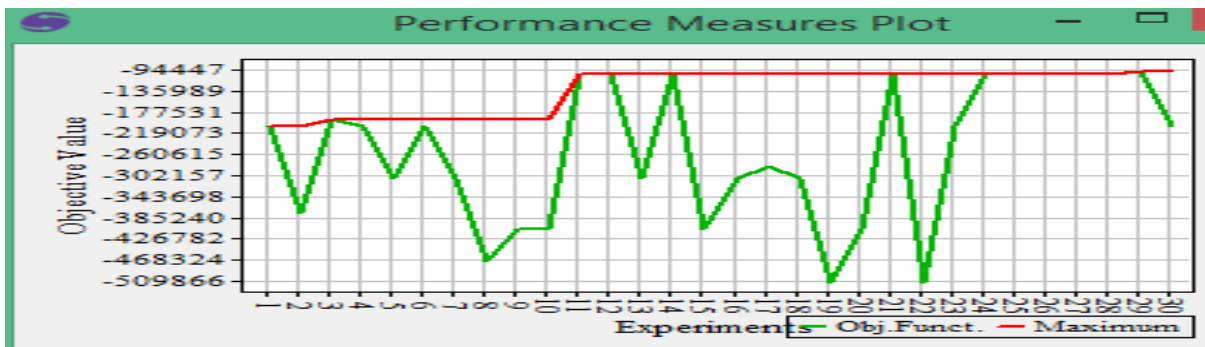


Figure F.3: Optimality second stage #2

Table F.1: Sample experimental runs - optimization

Experiment	Objective Function	QA_incoming: Total Cost (\$)	Res_QA_Incoming	Res_QA_Finished	Arr_Material	Arr_Tubes
12	413350.74	413350.74	1	2	36	12438
36	413364.523	413364.523	1.722	2.772	11110.574	1197.954
30	413364.523	413364.523	1.393	2.799	8781.148	16928.751
31	413364.523	413364.523	1.939	2.406	1795.18	21995.186
58	413364.523	413364.523	1.23	2.605	7800.893	9872.563
54	413411.387	413411.387	1.543	4.274	2541.969	11300.118
60	413411.387	413411.387	1.065	3.461	17950.027	7460.309
68	413411.387	413411.387	1.466	4.552	3336.215	18522.547
69	413411.387	413411.387	1.906	4.401	9880.647	24810.715
65	413414.143	413414.143	1.822	1.432	16189.198	17530.757
55	413414.143	413414.143	1.459	1.389	18343.841	23812.098
66	413414.143	413414.143	1.323	1.03	13704.038	19096.229
23	413499.6	413499.6	1	1	36	36
63	826786.937	826786.937	2.983	4.482	11879.167	16975.768
8	826786.937	826786.937	2	4	19440	24840
35	826786.937	826786.937	2.361	4.43	14890.305	18669.018
37	826786.937	826786.937	2.452	4.162	4073.664	14790.073
3	826795.207	826795.207	2	4	36	6237
51	826836.557	826836.557	2.232	1.889	15977.662	9507.345
50	826905.473	826905.473	2.26	3.559	1948.43	11221.122

Table F.1 (Continued)

Experiment	Objective Function	QA_incoming: Total Cost (\$)	Res_QA_Incoming	Res_QA_Finished	Arr_Material	Arr_Tubes
17	826946.823	826946.823	2	5	36	18639
67	826949.58	826949.58	2.853	2.596	1967.923	16634.3
5	826963.363	826963.363	2	2	9738	6237
49	826963.363	826963.363	2.445	2.709	18616.794	18251.506
59	826963.363	826963.363	2.24	2.683	11443.811	16690.552
57	826963.363	826963.363	2.948	2.571	4627.355	24549.754
25	826999.2	826999.2	2	3	36	36
11	1240104.597	1240104.597	3	1	19440	6237
15	1240104.597	1240104.597	3	1	14589	12438
44	1240104.597	1240104.597	3.225	1.783	10543.224	13419.284
47	1240104.597	1240104.597	3.868	1.128	14984.956	23383.704
46	1240104.597	1240104.597	3.027	1.668	10403.05	1474.442
62	1240104.597	1240104.597	3.927	1.111	9022.401	19294.1
29	1240104.597	1240104.597	3.489	1.018	11994.819	23304.384
6	1240104.597	1240104.597	3	1	14589	24840
38	1240253.457	1240253.457	3.84	3.959	15162.63	21654.922
14	1240253.457	1240253.457	3	4	9738	12438
1	1240253.457	1240253.457	3	3	4887	36
42	1240253.457	1240253.457	3.909	4.761	18544.948	6907.431

Table F.1 (Continued)

Experiment	Objective Function	QA_incoming: Total Cost (\$)	Res_QA_Incoming	Res_QA_Finished	Arr_Material	Arr_Tubes
41	1240253.457	1240253.457	3.185	3.457	18382.189	12381.376
34	1240253.457	1240253.457	3.808	4.933	11599.132	24228.183
32	1240253.457	1240253.457	3.632	4.717	15185.345	20214.827
33	1240253.457	1240253.457	3.462	4.526	9800.859	9276.872
24	1240253.457	1240253.457	3	5	14589	18639
26	1240256.214	1240256.214	3	2	19440	6237
48	1240256.214	1240256.214	3.861	2.54	5073.423	4854.576
56	1240256.214	1240256.214	3.667	2.771	16946.875	21599.38
19	1240344.427	1240344.427	3	4	36	6237
13	1240377.507	1240377.507	3	2	36	6237
39	1653659.33	1653659.33	4.345	1.842	3800.119	5632.643
45	1653659.33	1653659.33	4.366	1.356	17676.888	6604.731
43	1653659.33	1653659.33	4.742	1.72	12307.097	15177.212
22	1653659.33	1653659.33	4	1	19440	24840
4	1653659.33	1653659.33	4	1	9738	24840
9	1653670.357	1653670.357	4	4	36	6237
52	1653686.897	1653686.897	4.544	1.453	2256.977	22814.91
21	1653742.03	1653742.03	4	4	19440	6237
16	1653742.03	1653742.03	4	4	9738	6237

Table F.1 (Continued)

Experiment	Objective Function	QA_incoming: Total Cost (\$)	Res_QA_Incoming	Res_QA_Finished	Arr_Material	Arr_Tubes
61	1653742.03	1653742.03	4.84	4.662	9315.11	16095.97
40	1653742.03	1653742.03	4.446	3.27	6618.665	2073.293
53	1653742.03	1653742.03	4.891	4.191	10061.918	15246.903
64	1653802.677	1653802.677	4.716	1.58	460.292	24477.884
2	2067078.987	2067078.987	5	4	36	12438
27	2067128.607	2067128.607	5	4	9738	18639
20	2067128.607	2067128.607	5	5	19440	24840
18	2067128.607	2067128.607	5	4	4887	18639
10	2067128.607	2067128.607	5	5	14589	18639
7	2067128.607	2067128.607	5	5	14589	12438
28	2067238.874	2067238.874	5	3	36	6237

Table F.2: Sample experimental runs – optimization #2

Experiment	Objective function	Product : total exit	PreWeight: total cost	Arr_material	Arr_tubes	Res_RA_Incoming
29	- 94447.04	1606	96053.04	36	18639	1
25	- 99412.88	1678	101090.88	14589	18639	1
24	- 99412.88	1678	101090.88	9738	36	1
11	- 99412.88	1678	101090.88	14589	12438	1
12	- 99412.88	1678	101090.88	19440	6237	1
28	- 99412.88	1678	101090.88	14589	6237	1
14	- 99412.88	1678	101090.88	9738	6237	1
27	- 99412.88	1678	101090.88	19440	12438	1
21	- 99412.88	1678	101090.88	9738	18639	1
26	- 99412.88	1678	101090.88	9738	12438	1
3	- 189308.44	1619	190927.44	36	12438	2
1	- 203382.16	1694	205076.16	9738	12438	2
30	- 203382.16	1694	205076.16	14589	6237	2
6	- 203382.16	1694	205076.16	19440	6237	2
23	- 203382.16	1694	205076.16	14589	24840	2
4	- 203382.16	1694	205076.16	14589	36	2
17	- 280648.92	1617	282265.92	36	18639	3

Table F.2 (Continued)

Experiment	Objective function	Product : total exit	PreWeight: total cost	Arr_material	Arr_tubes	Res_RA_Incoming
5	- 305035.76	1708	306743.76	14589	36	3
18	- 305035.76	1708	306743.76	14589	18639	3
16	- 305035.76	1708	306743.76	9738	12438	3
13	- 305035.76	1708	306743.76	4887	36	3
7	- 305035.76	1708	306743.76	9738	6237	3
2	- 373463.84	1618	375081.84	36	24840	4
9	- 405927.04	1688	407615.04	19440	24840	4
20	- 405927.04	1688	407615.04	14589	6237	4
15	- 405927.04	1688	407615.04	4887	12438	4
10	- 405927.04	1688	407615.04	9738	6237	4
8	- 468175.68	1620	469795.68	36	18639	5
22	- 509866.08	1686	511552.08	4887	24840	5
19	- 509866.08	1686	511552.08	4887	6237	5

G. Hypothesis Test Summary

Table G.1: ANOVA single factor

ANOVA: Single Factor						
SUMMARY						
Groups	Count	Sum	Average	Variance		
Delivery_Flex	985	29100.11	29.54325888	142.3893846		
Mix_Flex	992	29363.252	29.60005242	141.116826		
Innovation_Flex	992	29338.083	29.57468044	139.8366681		
Volume_Flex	659	19531.933	29.63874507	142.67422		
ANOVA						
Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	3.949856131	3	1.31661871	0.009311631	0.99877	2.60736
Within Groups	512415.704	3624	141.3950618			
Total	512419.6538	3627				

H. Validation

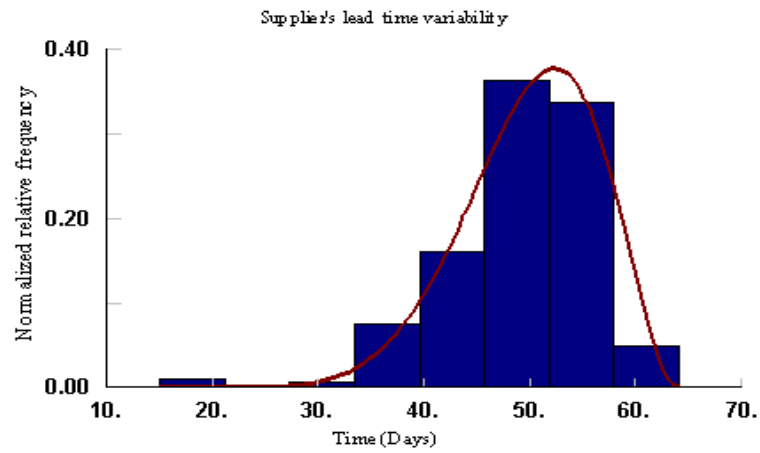


Figure H.1: Supplier's lead time variability

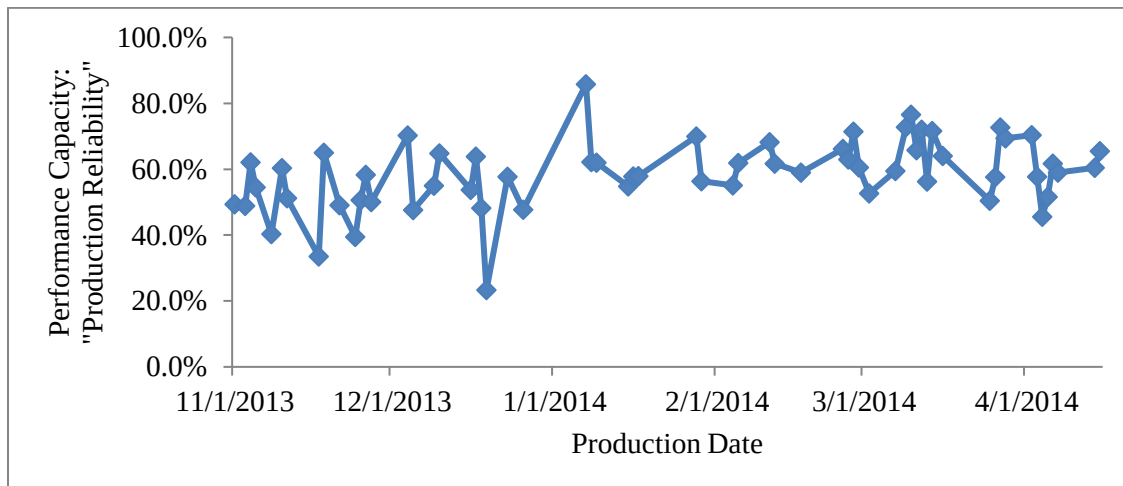


Figure H.2: Seasonality of demand pattern #1

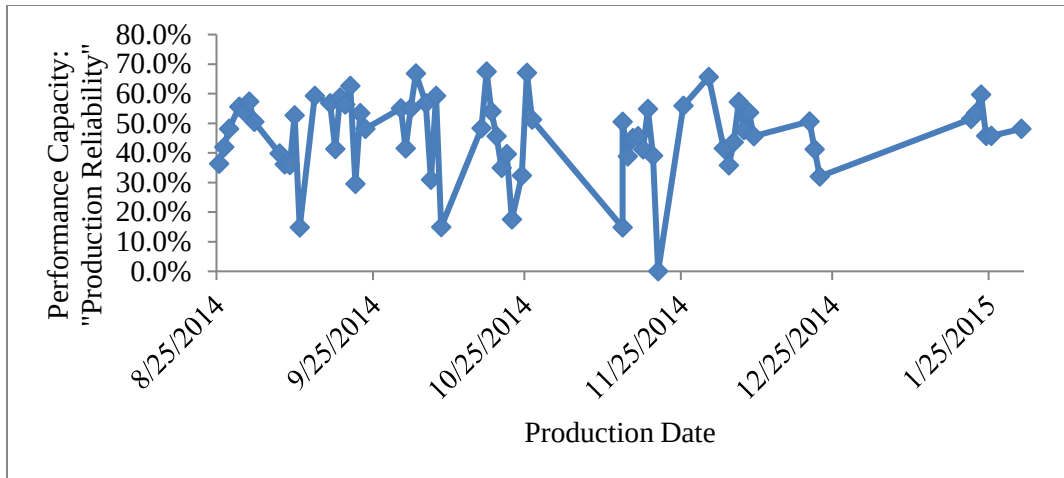


Figure H.3: Seasonality of demand pattern #2

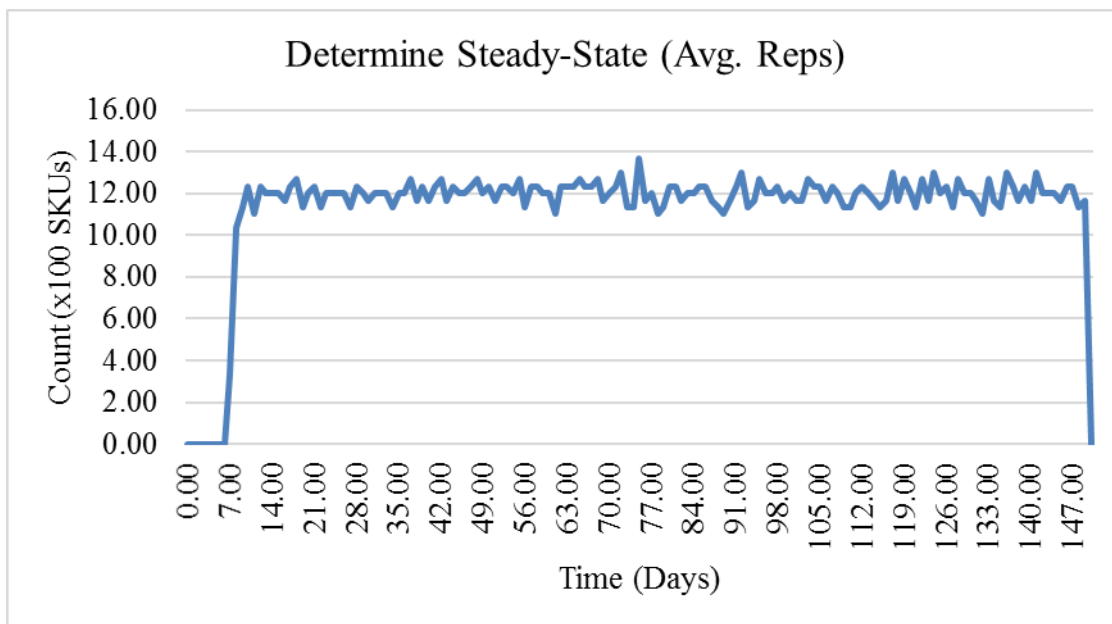


Figure H.4: Determine Steady-State

Buffer	Capacity	Batching Entity/ Attribute	Qty	Builder Logic	Notes
Caps_Inventory	Infinite			<pre> If (GroupQty(Packaging) <= 36) { Order 36 Caps To Receiving_QA_Caps Order 36 Caps To Receiving_QA_Buttons Order 36 Caps To Receiving_QA_Mech } </pre>	
Buttons_Inventory	Infinite				
Mech_Inventory	Infinite				
Packaging_Inventory	Infinite			<pre> If (Entity() = Packaging) { Send 36 Packaging To Production } Inc (vCountProducts) While (Entity() = Products) Do { If (vCountLipstics = 4400) { Send 4400 ProductC To Distribution } Else If (vCountProducts >= 4400 And vCountLipstics <= 14400) { Send 14400 ProductB To Distribution } Else If (vCountProducts >= 28800) { Send 28800 ProductA To Distribution } } Dec (vCountProducts) </pre>	Lipstick products are accumulated into A, B, and C SKUs: ProductA, ProductB, and ProductC respectively. When the stocked to the needed qty, signal is alerted for shipment. Batching is coded as accumulate by product/entity type.
Products_Inventory	Infinite	ProductA	28800		
		ProductB	14400		
		ProductC	4400		
CasePack_Inventory	Infinite			<pre> If (vQtyCpShipped <= vCountProducts) { Order 150 Blended_Shade To Production } Else { Wait 0.5 day } </pre>	
ShelfPack_Inventory	Infinite				

Figure H.5: Prioritizing and batching logic

ID	Text...	ption
Res_QA_Incoming	3.0000000	Scena ^
Res_Blender	1.0000000	Scena
Res_Weight	6.0000000	Scena
Res_Production	20.0000000	Scena
Res_QA_Finished	1.0000000	Scena
Res_Warehouse	1.0000000	Scena
PT_QA_Raw	Wait U(1,0.5) day	Scena
PT_Weight	Wait U(1,0.5) hr	Scena
PT_Blend	Wait T(3,5,10) min	Scena
PT_Assly	Wait U(2,1) min	Scena
PT_FinalQA	Wait T(1,2,3) hr	Scena
PT_Distribution	Wait U(2,1) min	Scena
Arr_Tubes	12438.0000000	Scena
Arr_Material	9738.0000000	Scena

Figure H.6: Expressions Setup

Parameters	Baseline	VF_mfg	MF_mfg	DF_mfg	NF_mfg
Simulate Scenario?	☒	☒	☒	☒	☒
Last Simulation Run	4/15/2020 4:36:19 PM				
Res_QA_Incoming	3.0000000	2	2	2	2
Res_Blender	1.0000000	1	1	1	1
Res_Weight	6.0000000	1	1	1	1
Res_Production	20.0000000	1	1	1	1
Res_QA_Finished	1.0000000	4	1	1	1
Res_Warehouse	1.0000000	1	1	1	1
PT_QA_Raw	Wait U(1,0.5) day	Wait U(1,0.5) day	Wait U(1,0.5) day	Wait U(1,0.5) day	Wait U(1,0.5) day
PT_Weight	Wait U(1,0.5) hr	Wait U(1,0.5) hr	Wait U(1,0.5) hr	Wait U(0.5,0.25) hr	Wait U(2,1) hr
PT_Blend	Wait T(3,5,10) min	Wait T(3,5,10) min	Wait T(3,5,10) min	Wait T(3,5,10) min	Wait T(3,5,10) min
PT_Assly	Wait U(2,1) min	Wait U(2,1) min	Wait U(2,1) min	Wait U(2,1) min	Wait U(2,1) min
PT_FinalQA	Wait T(1,2,3) hr	Wait T(0.16,2.4) hr	Wait T(0.16,2.4) hr	Wait T(0.16,2.4) hr	Wait T(0.16,2.4) hr
PT_Distribution	Wait U(2,1) min	Wait U(2,1) min	Wait U(2,1) min	Wait U(2,1) min	Wait U(2,1) min
Arr_Tubes	12438.0000000	12420	12420	12420	12420
Arr_Material	9738.0000000	9720	9720	9720	9720

Figure H.7: Settings of scenarios

Table H.1: Model validation – scenario analysis

Flexibility Dimensions	Metrics	Scenarios			Effect on TH/CT
		Baseline	Scenario 1	Scenario 2	
Volume	PR (%)	65	80	100	
			↑33%	↑52%	TH
			↓10%	↓13%	CT
Mix	Changeover (hours)	U [0.5,1]	U [0.4,0.5]	U [0.2,0.3]	
	PR @65		↑33%	↑52%	TH
	PR @65		↓10%	↓13%	CT
Delivery	Lead time (days)	50	40	30	
	PR @65		↑18%	↑28%	TH
	PR @65		↓11%	↓59%	CT
Innovation	Batch Size	36	40	50	
	PR @65		NSC	NSC	TH
	PR @65		NSC	NSC	CT

Table H.2: Sample data – simulation output validation

Time point	Sim. TH	Actual TH
1	113.3	135
2	123.3	95
3	110	164
4	123.3	124
5	120	120
6	120	87
7	120	67
8	123.3	121
9	113.3	90
10	120	77
11	120	125

Vita

Wolday Desta Abrha was born in Hawzen, Ethiopia, to the parents of Amete Gidey (mother) and Desta Abrha (father). He is the youngest of five siblings. Wolday graduated from Agazi Comprehensive High (with very great distinction) in Adigrat, Ethiopia in 1996. He obtained a Bachelor of Science in Industrial Engineering (BSIE) in 2001 from Mekelle University (MU), as top 5 among the pioneer BSIE graduates in Ethiopia. Wolday started his professional career by accepting an engineer position at Messebo Cement Factory in Mekelle, Ethiopia in August 2001, and worked there until September 2003. Wolday joined back to MU as Instructor in July 2003 with a vision to giveback pragmatic education and advance his studies. He moved to the United States in 2005, accepted a graduate teaching assistantship in Engineering Technology Department at Middle Tennessee State University, where he graduated with Master of Science in Engineering Technology in 2007. He worked in the automotive manufacturing industry with Allegis Group, holding Quality Engineering positions for about four years until he enrolled in Ph.D. – Industrial Engineering at the University of Tennessee, Knoxville in August 2012. Over the course of his Ph.D. study, Wolday has been actively involved in research projects and executive training to industry partners, as part of his graduate research assistant responsibility. In August 2017, he accepted a visiting faculty role at the Department of Engineering Management & Technology at University of Tennessee in Chattanooga, where he is currently working. Wolday specialized in modeling supply chain flexibility and graduated in August 2020.