Optimizing The Global Performance Of Build-to-order Supply Chains

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OPTIMIZING THE GLOBAL PERFORMANCE OF BUILD-TO-ORDER SUPPLY CHAINS

by

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A dissertation submitted in partial fulfillment of the requirements
for the degree of Doctor of Philosophy
in the Department of Industrial Engineering and Management Systems
in the College of Engineering and Computer Science
at the University of Central Florida
Orlando, Florida

Fall Term
2006

Major Professor: Christopher D. Geiger

ABSTRACT

Build-to-order supply chains (BOSCs) have recently received increasing attention due to the shifting focus of manufacturing companies from mass production to mass customization. This shift has generated a growing need for efficient methods to design BOSCs. This research proposes an approach for BOSC design that simultaneously considers multiple performance measures at three stages of a BOSC – Tier I suppliers, the focal manufacturing company and Tier I customers (product delivery couriers).

We present a heuristic solution approach that constructs the best BOSC configuration through the selection of suppliers, manufacturing resources at the focal company and delivery couriers. The resulting configuration is the one that yields the best global performance relative to five deterministic performance measures simultaneously, some of which are nonlinear. We compare the heuristic results to those from an exact method, and the results show that the proposed approach yields BOSC configurations with near-optimal performance. The absolute deviation in mean performance across all experiments is consistently less than 4%, with a variance less than 0.5%.

We propose a second heuristic approach for the stochastic BOSC environment. Compared to the deterministic BOSC performance, experimental results show that optimizing BOSC performance according to stochastic local performance measures can yield a significantly different supply chain configuration. Local optimization means optimizing according to one performance measure independently of the other four. Using Monte Carlo simulation, we test the impact of local performance variability on the global performance of the BOSC. Experimental results show that, as variability of the local

performance increases, the mean global performance decreases, while variation in the global performance increases at steeper levels.

To our beloved Messenger Mohammad, peace and prayer upon Him, the messenger of love and peace, the most noble and the greatest mercy and guidance from Allah the Almighty to all mankind

ACKNOWLEDGMENTS

I believe behind every great achievement stand great, invisible hearts, minds and hands. For that, I would like to acknowledge the ones who were the main drivers for my success and achievement.

First and foremost, I would like to thank Allah the Almighty for helping me reach this stage in life and achieve all the success and contributions I made to date. I pray and ask Him for His forgiveness, His mercy and I pray to Him to bless me with a happy good ending. (Amen)

I would also like to thank my advisor, Dr. Christopher D. Geiger. He managed the scope of this dissertation and was a solid, steady, reliable footing for me throughout as I worked through the process of conducting this research. He guided not only this dissertation but provided advice about my career, interviewing, and plans after my completion. Dr. Geiger is professional, has noble work ethics, and is organized, reliable, responsible and kind, the best advisor one could have. Ours is a partnership. He lets me be who I am. I am eternally grateful to have found him and to have been his student and his advisee.

I am grateful to have the fine members on my committee. Dr. Yasser Hosni's diligence, thoroughness, and interest were evident throughout this process. Thank you, Dr. Hosni, for your meaningful questions and your detailed review. This is an improved dissertation because of it. Special thanks to Dr. Linda Malone who was very helpful and guided me a lot through the flow of my work. Her experience and knowledge helped me to finish this dissertation in this timely, efficient manner. She provided me with guidance and helped me a lot in designing the experiments and the statistical analysis and validation of my results. I am also very grateful to Dr. Angappa Gunasekaran for his valuable ideas and questions that kept me alert and improved my breadth of knowledge and understanding of the core topic of my dissertation. Nevertheless, his leading journal papers in the core field of this research were the inspiration and the source of evidence to the research gap that led this whole research. I am also grateful to Dr. Mohamed Fayez who helped me understand the Supply Chain Operations Reference model. His guidance, valuable discussions and advice helped me very much in the preliminary stages of this dissertation. I also like to thank Dr. Luis Rabelo for being the first to advise me to conduct my research in the area of supply chain management. I also like to thank my friends Pradeep Aeluri and Harish Ramakrishnan for helping me in the C coding and programming of the heuristic approaches that I proposed in this research. Nevertheless, I would like to sincerely thank my friend Dr. Mohammad Feras. He provided me with his time and opinion several times and on many occasions. He listened to my ideas and provided me with guidance and advice.

I would also like to acknowledge the following two researchers in their fields who both generously shared materials, answered my many questions, and showed interest in this dissertation. Dr. Yunus Kathawala for post mailing me a hard copy of his leading and most updated journal paper even before it is released for publication, and Mr. Jani Kilpi, from Finnair who provided thorough and technical answers for all my questions through electronic mail.

I also would like to thank Dr. Ronald Eaglin and Dr. Amr Oloufa for their financial support and for providing me with research assistantships through the whole journey of obtaining my PhD. Without their support, I would not have been able to obtain my tuition waivers. I would also like to express my sincere thanks to Dr. Ahmad El-Shennawy for his valuable mentoring, caring and advice through the whole process of obtaining my PhD. He also provided me with all the encouragement and support a student could get from an academic professor. Nevertheless, I would also like to extend a special thanks to Dr. Nabeel Yousef for all his kindness and unlimited support. He was my elder brother and my friend and was always the first helping hand I received whenever needed.

Moreover, I would like to express my sincere and humble thanks to my great beloved parents, Mohamed Shaalan and Qout Al-Qoloub Shaalan for all their support, love, encouragement and sacrifice. For both of you, the ink of the world are not enough to express my gratitude and respect. You are the best parents any one could ever wish to have. I thank Allah the Almighty that He blessed me with loving and respectful parents like you. I would also like to thank my sincere aunt Fekreya Shaalan. I am blessed from Allah with a second loving mother like you. I appreciate all your kindness, your sincere love and caring. You never stopped praying to Allah for me to guide me to all the best, and you always feel happy for my success deeply from the bottom of your heart. You always make me feel that you are my second mother and you always treat me like your own son. My sincere and deepest gratitude to you.

I also would like to thank all my friends and colleagues, especially my honorable and respectful roommate and friend Mr. Ali Bayat, who was always supportive and a real friend in need. His good friendship and responsible character made me feel I am living with my brother in our own home.

And, last but not least, I would like to thank my beloved fiancée Dima Cheaib. All my gratitude and love to you, my darling. You believe in my abilities and you always provide me with love and encouragement. You are always patient, understanding, loving and supportive. Without you, my love, I would have never been able to make it through all the tough times and situations I have been through during this long journey.

I am sure there are hundreds of people I would like to acknowledge for adding a remarkable contribution to my success and helping me to become who I am now, *i.e*, Mr. Samir Adawi, uncle Farouk Shaalan, my Nany Amna, my beloved sisters Ghada and Asia, my beloved brother Yaseen, my beloved brother-in-law Dr. Khaled El-Kilany, and my best friends Karim El-Barshoumy, Amr El-Feky and Moataz Abdel Wahab. I believe I need the size of this dissertation to acknowledge every significant helping hand that I received through my whole life journey.

I pray to Allah to reward and bless every name mentioned above and all who helped me to be who I am now. (Amen)

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CHAPTER 1: INTRODUCTION

1.1. Background

Before reaching the customer, products must pass through a sophisticated system of integrated activities that comprise the product processing cycle that is referred to as the *value chain*. The value chain is described as the collection of interconnected activities utilized by a business in order to produce and sell its products and services (Chase 2001; Porter 1985; Bolstroff 2005). Chase (2001) and Porter (1985) state that the value chain has three major sections, *i.e.*, the supply chain, the demand chain and the support chain. The demand chain and the support chain have similar structure within all value chains. However, the structure of supply chains vary from manufacturing to service value chains. Figure 1.1 shows a typical manufacturing value chain.

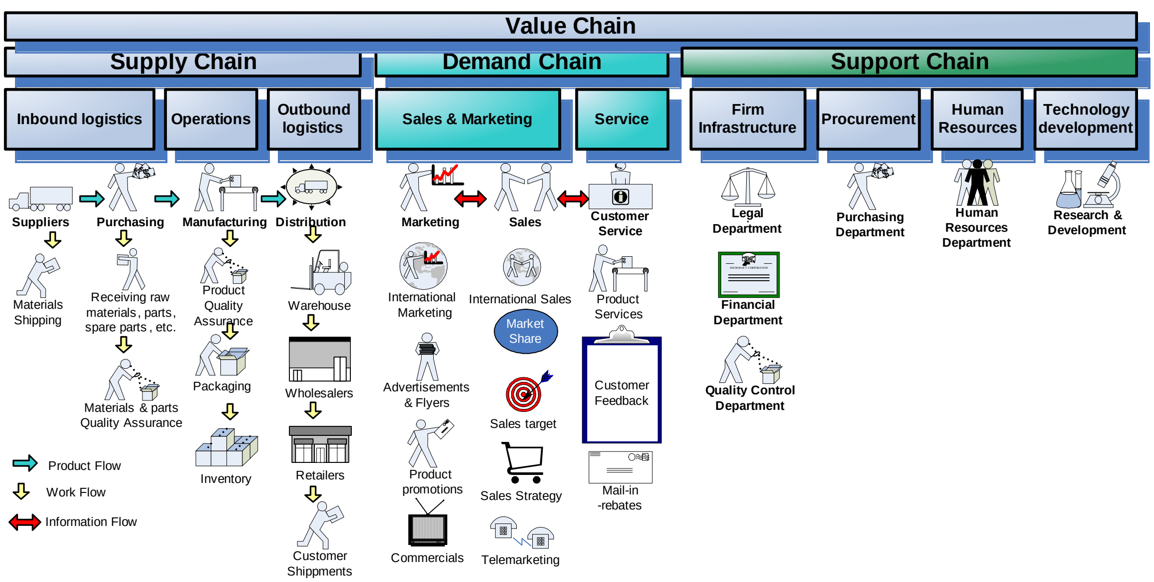

Figure 1.1. General value chain for a manufacturing organization.

The *supply chain* is the network of suppliers and purchasing inbound logistics, the production and processing operations, and the product distribution outbound logistics. The *demand chain* includes Marketing, Sales and other services that help generate and characterize market demand for products and services. *Support chains* include all supporting processes for both the supply chain and the demand chain such as Research and Development, Human Resources and Legal Services. The management of the supply chain section of a manufacturing value chain is the focus of this research investigation. A manufacturing supply chain is a complex network of integrated interactions among entities that describe the processing and flow of materials, products (and services), information and cash. This processing and flow are triggered by rising customers' needs, and they aim to satisfy customer demand and expectations, while sustaining net profitability among all entities in the supply chain network.

1.2. Manufacturing Supply Chains

Figure 1.2 shows the primary components of a manufacturing supply chain and the interactions in the logistics network of the supply chain. Manufacturing firms often try to extend their interests beyond their organizational boundaries to form partnership with various business partners and suppliers in order to perform more efficiently and economically. As a result, interest in the design and management of the global supply chain, by not only practitioners but also researchers, has increased dramatically (Chase 2001).

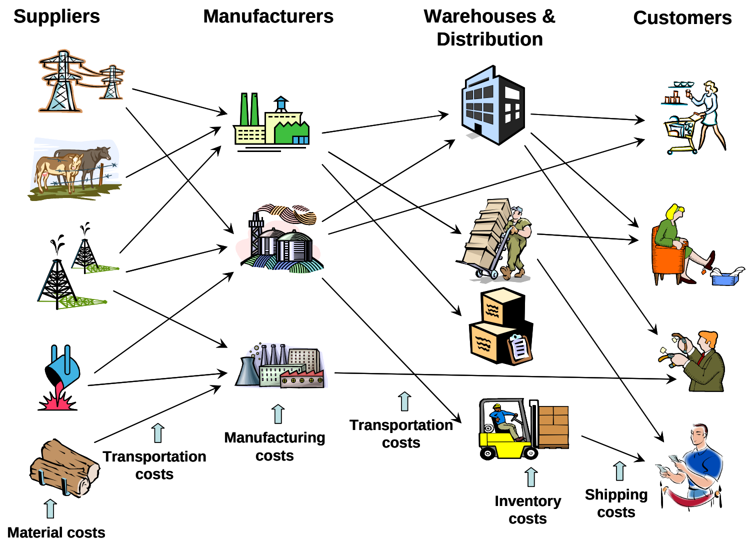

Figure 1.2. Example of a manufacturing supply chain network (adapted from Simchi-Levi *et al.* (2004) Figure 1-1. The logistics network. p. 2).

Typically, there are large investments associated with supply chain operation and coordination, where a significant portion of these investments is a result of high waste and ineffective management practices. Simchi-Levi *et al.* (2004) believe that these investments are due to inefficient strategies, waste, redundancies and unnecessary cost components. For example, experts believe that the US grocery industry alone could reduce approximately about 10% of its annual operating costs (or approximately $30 billion) if more efficient supply chain strategies are utilized (Simchi-Levi *et al.* 2004). Figure 1.3 shows the US-related supply chain expenditure from 1998-2002, which averaged approximately $939 billion over the four years and contributed about 10% to the US gross national product in 2000.

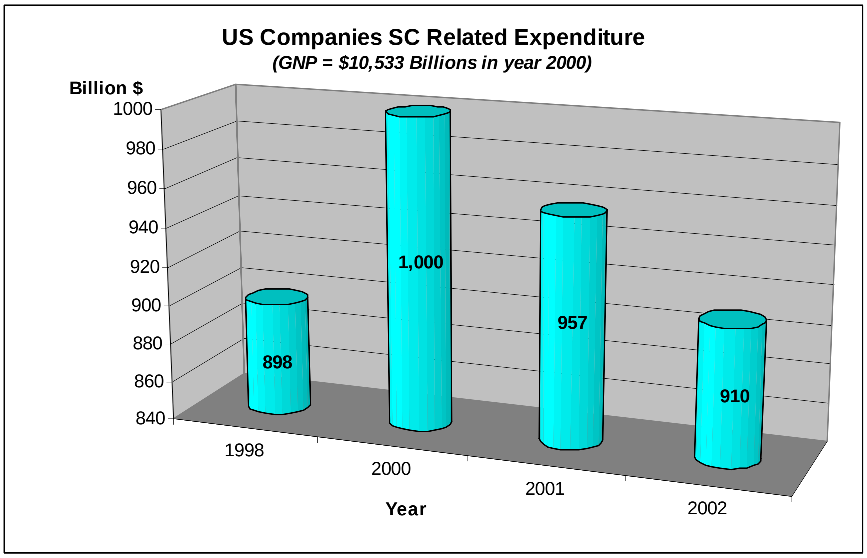

Figure 1.3. Supply chain-related expenditure by US companies (source: Simchi-Levi *et al.* (2004) and Scaruffi (2005)).

Due to these exorbitant costs, interest in supply chain design, analysis and optimization has increased rapidly over the past decade, while ways to better manage the supply chain has attracted the interest of not only academicians but also CEOs and business practitioners (Vondrembse *et al.* 2005).

1.3. The Emergence of the Agile Supply Chain

Black (2002) states that the manufacturing focus of 1980s was quality and the 1990s were active in the globalization and merging of large enterprises. Black (2002) goes on to suggest that the first decade of 2000 is defined by velocity. In other words, in the 21st century, manufacturing organizations will compete in terms of supply chain responsiveness to changes in customer demand and market variations, in particular, unexpected variation.

A traditional manufacturing supply chain has been commonly associated with make-to-stock or build-to-forecast mass production systems managed primarily based on sales forecasts, where all products are "pushed" to downstream processes (Gunasekaran and Ngai 2005; Howard *et al.* 2005; Sharma and LaPlaca 2005; Anderson 2003). This approach ultimately provides the customers with standard, rigid non-customized products. However, this philosophy has changed due to severe competition in the current global marketplace. In addition to the development and manufacture of products with shorter lifecycles, the increase in customer's expectations, the reduced barriers to international trade, free trade agreements, globalization and the inclination towards outsourcing are among the major drivers that have influenced businesses to convert their traditional manufacturing and supply chain systems into more flexible and responsive supply chains, or *agile supply chains*.

Lou *et al*. (2004) define agility as the "…ability to quickly respond to market changes," where the authors state that it is a major factor for enterprise success in the market. Also, Gunasekaran and Ngai (2005) define the agility of a supply chain as its "…flexibility and responsiveness." Hence, an agile supply chain can be considered as one that can readily adapt to unexpected market variations and benefit from fast delivery of products and services to customers, lead time flexibility, utilizing new information transfer technologies (*e.g.*, radio frequency identification) in order to transfer information faster and be able to make better decisions (Vondrembse *et al*. 2005). The ongoing advancement in communications, information technology, and transportation methods contribute significantly to the aforementioned increasing interest and development of new management methods for the agile-based supply chain.

1.4. Build-to-Order Supply Chains

The build-to-order (BTO) concept is known to be initially introduced by the Association for Manufacturing Excellence (AME) in 1998 (Anderson 2003). According to Anderson (2003), build-to-order is defined as:

> "….the capability to quickly build standard products upon receipt of spontaneous orders without forecasts, inventory, or purchasing delays. These products may be shipped directly to individual customers, to specific stores, or as a response to assemblers' pull signals (Assemblers' signals that certain parts are needed right away for assembly)" (Anderson 2003).

In other words, build-to-order can be briefly summarized as the on-demand production of standard configurable products with minimal inventories and forecasts.

According to Vondrembse *et al.* (2005) and Gunasekaran and Ngai (2005), a build-to-order supply chain (BOSC) is one agile supply chain management system that has received considerable interest in research and in industry. The BOSC has been successfully implemented in many enterprises such as Dell, HP Compaq and BMW (Gunasekaran and Ngai 2005). However, BOSC suppliers may need to utilize spontaneous BTO strategies to respond to the pull signals of the focal company. However, if suppliers cannot actually build parts on-demand, they will be tempted to meter them out from inventory. This, in essence, transfers the focal company's work-in-process inventory to their finished goods inventory (Anderson 2003).

Table 1.1 compares traditional build-to-forecast supply chains (BFSCs) and BOSCs along several dimensions, as defined by Gunasekaran and Ngai (2005) and Sheikh (2003). In BFSCs, long lead times for supplier order fulfillment are typical. While, in BOSCs, the network is designed such that suppliers deliver their raw materials from supplier parks, where component manufacturers and suppliers are co-located with key original equipment manufacturers in order to improve the delivery and servicing reliability within the supply chain. This tends to lead to reduced raw material and component supply lead times compared to those of BFSCs. In addition, the holding costs and inventory risks associated with material inventory with respect to the manufacturer and suppliers are minimized.

Table 1.1. Comparison of build-to-forecast supply chains and build-to-order supply chains.

Dimension	Build-to-Forecast Supply Chains	Build-to-Order Supply Chains
Marketing	Push-based	Pull-based
Logistics	Mass approach	Fast, reliable, customized
Sales	Sell from stock	Build to customer order
Product Configuration	Low variety of options	High variety of options
Production	Focus on level and stable schedules	Customer demand focused on supply chain flexibility
Tier 1 Suppliers	Mainly long lead times	Collaborative, responsive
Product Delivery Time	Shorter delivery time	Longer delivery time
Managing Demand Uncertainty	Safety stock of sales products	Strategic part buffers and information management
Finished Good Inventory	High stock control	Low, condensed dealer stock levels
Customer Relationship	Dealer-owned	Shared across the extended enterprise
Order Promising Is Subject To:	Availability of finished product inventory	Availability of manufacturing capacity
Purchase Orders	Through retailers and distributors	Directly from manufacturer
Market Demand	Reactively respond to stabilized market demand by providing only standardized products in their maturity lifecycle phase	Allow manufacture to react on time with the market demand and even shape the behavior of the market
Product Lifecycle	Long	Short

In BFSCs, customer demand uncertainty for the finished products is addressed by managing large buffer stocks of finished products downstream of the supply chain. In BOSCs, customer demand uncertainty is handled by buffering adequate level of strategic parts and subassemblies that require large replenishment times at Tier 1 suppliers. After receiving a customer order, the partially-completed components and subassemblies are outsourced in order to produce a customized final product according to the specifications given in the customer order.

1.5. Motivation of Research

After a supply chain is configured, researchers and practitioners focus on methods to improve supply chain performance given the initial configuration (Piramuthu 2005). However, the advancements of internet and global communication technologies, free trade agreements and outsourcing have created an environment of high competition. This intense competitive environment has created a need for developing methods for evaluating the global supply chain performance right from the start. In particular, the optimization of the supply chain global performance by dynamic reconfiguration of the supply chain processes and entities has been a focus.

As previously mentioned, supply chain demand and performance are stochastic in nature. Hence, BFSC practitioners have always managed to introduce buffer stocks downstream at the bottlenecks to accommodate for variability. The introduction of buffer stocks to divide the global supply chain at the buffer stocks into several dyadic or chain links. Then, the performance of the processes within these smaller links are individually optimized on the local level. As a result, researchers and practitioners optimize the global performance measures for the supply chain focusing on optimizing the local measures of supply chain links separately. The problem becomes more essential for the BOSCs due to their lean nature and the minimal buffer stocks and lack of inventories along the BOSC, which does not allow the subdividing of the supply chain, as in the case of BFSCs. This necessitates the researchers and practitioners to optimize the global performance of the BOSC by studying the entire BOSC as a whole.

Moreover, in a BOSC, customer orders are typically unique, as they are associated with individually highly-customized products. Hence, any variation along the supply chain processes can adversely affect each order and cause delays in order processing and delivery to the customer. In addition, BOSCs are associated with short-term dynamics in supply and demand. Therefore, the improper management of unexpected variation along the supply chain would lead to customers' dissatisfaction and loss of profit (Krajewski *et al.* 2005). As a result, reducing and controlling variation in BOSCs is critical and can potentially produce more benefit than in BFSCs.

1.6. Goal of Research

The emergence of agile BOSCs has generated interesting developments in recent years; however, several areas remain to be investigated. The focus of the research is to design the build-to-order supply chain network based on the strategic selection of supply chain entities and resources, *i.e.*, selecting the primary Tier 1 parts suppliers, the manufacturing resources at the focal company and the Tier- 1 customers (product delivery couriers). The primary goal is to optimize the global performance measures, given a conflicting set of local, dynamic performance measures for each supply chain entity or resource.

Our specific research objectives are the following. We plan to derive several mathematical models based on multiple supply chain performance measures for which we will simultaneously seek to optimize. We suspect that many of these objective functions will be both linear and non-linear. We consider five commonly-accepted measures used by practitioners. These are supply chain cost, responsiveness, reliability, flexibility and asset management (SCC 2005).

Secondly, we develop heuristics to simultaneous optimize build-to-order supply chain performance according to the five performance measures. We first consider optimizing build-to-order supply chain performance under a deterministic scenario. Then, we seek to optimize supply chain performance under stochastic conditions, which are closer to real-world conditions.

1.7. Expected Contributions to Research Frontier and Industry Practice

To the best of our knowledge, currently there exists no methodology to quantitatively model variability in BOSCs on a strategic level not only during the design phase but also while managing the supply chain. The exploration of a framework for modeling and optimizing the global performance of a multi-objective, multi-echelon BOSC network contributes significantly to the area of supply chain network optimization on both the strategic and tactical levels. This exploration will provide researchers with a framework that will allow for future research for testing the impact of product lifecycle, technology lifecycle, human learning curves and the variation of BOSC processes and activities. In addition, this exploration of BOSC optimization will help in designing robust supply chains that are stable and adaptive to several sources of variation. Finally, this investigation will aid in detecting the variation within the supply chain in terms of several global performance measures simultaneously.

In practice, supply chain managers can benefit from the discoveries of this investigation by being able to quickly design supply chains for their build-to-order short life products, perform what-if analysis, and reconfigure the supply chain in case a supply chain resource is enters or exit the business market. The framework yielded from this research can help the supply chain to become more reliable and resistant to expected and unexpected sources of variation, potentially making it more manageable and perform more predictably. Furthermore, it will provide insight to the senior management about the overall performance of the supply chain in the presence of inherent variation according to five generally-accepted supply chain strategic and tactical performance measures (SCC 2005). Finally, the results of this investigation will help organizations see alternative solutions that provide reasonable secondary options that can be applied in case an unexpected, non-controllable event impact the current configuration of the supply chain, *i.e.*, wars, national security threats, safety-related issues, political instability in suppliers' countries, *etc*.

CHAPTER 2: LITERATURE REVIEW

2.1. Introduction

The manufacturing industry has gone three major shifts – craft (or artisan) production, mass production and Just-in-Time Manufacturing (JIT) (Womack *et al*. 1990; Kathawala and Wilgen 2005). Each manufacturing shift used different strategies that resulted in different production characteristics in terms of cost and product variety.

In craft (or artisan) production, manufacturing is carried as individual custom projects that are manufactured in a job-by-job basis. This type of manufacturing is characterized by providing the customer with a high variety of custom-tailored products at relatively higher costs.

The second shift is mass production, which started at the beginning of the Industrial Revolution with the introduction of Henry Ford's production assembly line for his standard Ford Model-T vehicles. This type of production was characterized by a push strategy in logistics and exchanged priorities from focusing on product variety to focusing on manufacturing costs. (Kathawala and Wilgen 2005; Henry Ford Organization 1995-1999). The third shift in manufacturing is the JIT philosophy, which was introduced in the early 1980s by the Japanese Toyota Motors Company (Monden 1983). This type of production was characterized by the lean manufacturing strategy, which focuses on waste minimization. This shift provides more cost reductions for the mass production systems.

During the 1990s and the first five years of this millennium, mass customization was introduced in different forms. In fact, several manufacturing strategies that fall under mass customization attempts to take advantage of the best characteristics from the three major manufacturing shifts, *i.e*, provide high product variety as in craft production, low product unit cost (due to economies of scale) as in mass production and minimized (inventory) wastes under the JIT philosophy. Figure 2.1 illustrates the three major shifts and their positive characteristics.

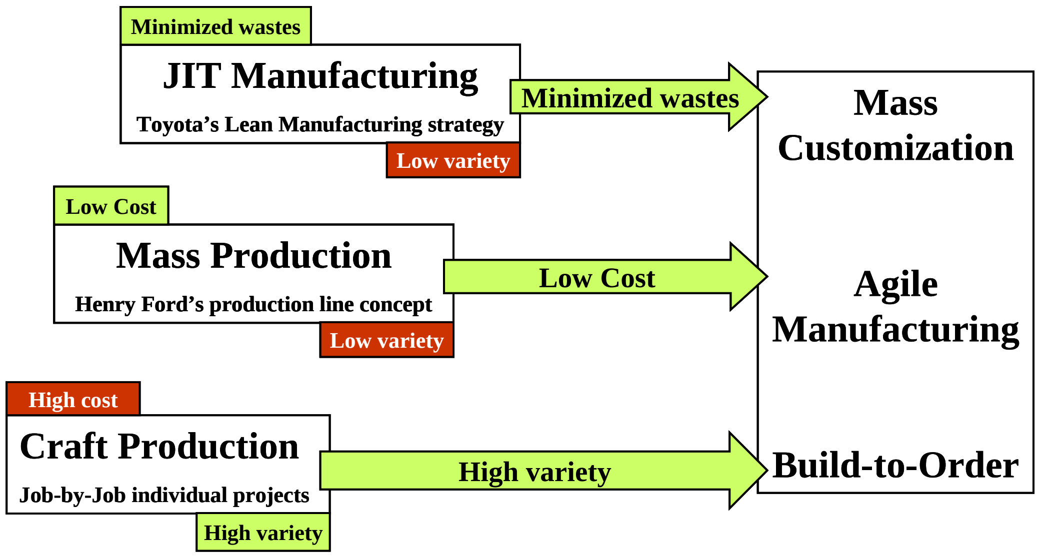

Figure 2.1. The major paradigm shifts in modern manufacturing.

In fact, the mass customization movement is simply a way for returning back to working under conditions similar to the craft (or artisan) production, while exploiting the modern advancements in technology in communication (*e.g.*, wireless and digital technology, internet), transportation (*e.g.*, air freight, railway, maritime carriers) and globalization (*e.g.*, free trade agreements such as the General Agreement for Trade and Tariff, the North American Free Trade Agreement, the European Union and the Asian Free Trade Agreement (AFTA), reduced or eliminated importation tax and custom barriers).

Figure 2.2 shows the categorization of the different manufacturing strategies referred to in research and practice. This categorization is either by mass production strategy or mass customization. The make-to-stock manufacturing strategy falls under the mass production paradigm. Under a make-to-stock strategy, final products are manufactured and perhaps stored before being assigned and delivered to any customer. As a result, large inventories of finished products are held in the system at several locations (*e.g.*, manufacturer warehouses, wholesalers and retailers. Hence, carrying costs are relatively the highest in this type of manufacturing environment. The response to varying customer demands is the lowest due to the manufacturing of standard products. Similarly, the response to product and process technology changes is the lowest, as the manufacturer needs to deplete existing inventories of older products and associated components and subassemblies before starting the production of the new product of newer technology.

Make-to-forecast is another strategy to falls under the mass production paradigm, where forecasting methods are adopted to predict the future demand for products. This strategy helps reduce the inventories of finished products by producing only according to forecasts, and thus eliminating the carrying costs of excessive inventories. However, the bullwhip effect and the forecast errors remain a challenge for supply chains that support this type of manufacturing environment (Forrester 1961).

The adoption of the deliver-to-order strategy, in which manufacturers are able to reduce the bullwhip effect resulting from wholesalers and retailers, reduce forecasting errors by selling directly to the end users. This type of strategy initiates the need for more agile and responsive supply chains, which researchers refer to as either lean supply chains, hybrid supply chains, spontaneous supply chains, or adaptive supply chain (Vondrembse *et al*. 2004).

The manufacturing strategies that fall under the mass customization paradigm are assemble-to-order, in which subassemblies are manufactured and stored in place of relatively more expensive finished products, make-to-order, in which production of individual customer orders are carried out by pulling from inventories of parts instead of subassemblies, and build-to-order, which is the focus of this research.

<table>
<tr><td></td><td colspan="6">Supply Chain Type</td></tr>
<tr><td></td><td colspan="2">Build-to-Forecast</td><td colspan="3">Lean/Hybrid/ Agile /Adaptive/ spontaneous</td><td>Build-to-Order</td></tr>
<tr><td>Manufacturing logistics goal</td><td colspan="3">Mass production</td><td colspan="3">Mass Customization</td></tr>
<tr><td>Manufacturing system Environment</td><td>Make-to-Stock</td><td>Make-to-Forecast</td><td>Deliver-to-Order</td><td>Assemble-to-Order</td><td>Make-to-Order</td><td>Build-to-Order</td></tr>
<tr><td>Product type</td><td colspan="3">Standard Products</td><td colspan="2">Hybrid Products</td><td>Configurable Agile Products</td></tr>
<tr><td>Manufacturing strategy</td><td colspan="3">Economy of scale</td><td colspan="3">Modularization, JIT
Delayed Product Differentiation</td></tr>
<tr><td>Logistics Flow</td><td colspan="2">Push</td><td colspan="4">Pull</td></tr>
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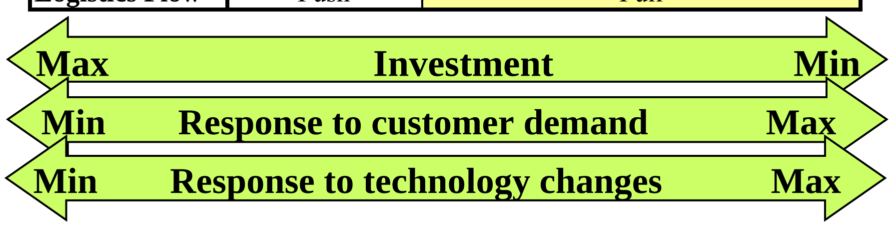


Figure 2.2. The categorization of modern manufacturing environments.

2.2. Supply Chain Management: Background and Definitions

Many supply chain researchers have proposed definitions of supply chain management. However, the definition of supply chain management itself remains subjective as there is no exact scientific definition that exists. According to Croom *et al.*

(2000), the inconsistent definitions of supply chain management is due to the fact that the supply chain has been addressed from several different perspectives. Croom *et al.* (2000) claim that the origin of the supply chain is from the early work of Forrester (1961), which led to the development of the techniques of industrial system dynamics. Stadtler (2005) suggests that the term supply chain management is introduced in the literature in 1982. Since that time, supply chain management has been the focus of several members of the research and industrial communities. However, management of the supply chain is still not clearly and completely understood (Croom *et al.* 2000). Many authors have addressed the need for a specific definition and conceptual framework for supply chain management (*e.g.*, Stadtler 2005; Haung *et al*. 2003; Cooper *et al.* 1997; Lambert *et al.* 1998; Fayez 2005).

The definition of supply chain management, as provided by the American National Standards Institute (ANSI), is:

> "…the logistics of managing the pipeline of goods from contractors with suppliers and receipt of incoming material, control of work-in-process and finished goods inventories in the plant, to contracting the movement of finished goods through the channel of distribution." (ANSI Standard Z94.0-2000).

Swaminathan and Tayur (2003) define supply chain management as:

> "…the efficient management of the end-to-end process, which starts with the design of the product or service and ends with the time when it has been sold, consumed, and finally discarded by the customer. This complete process includes product design, procurement, planning and

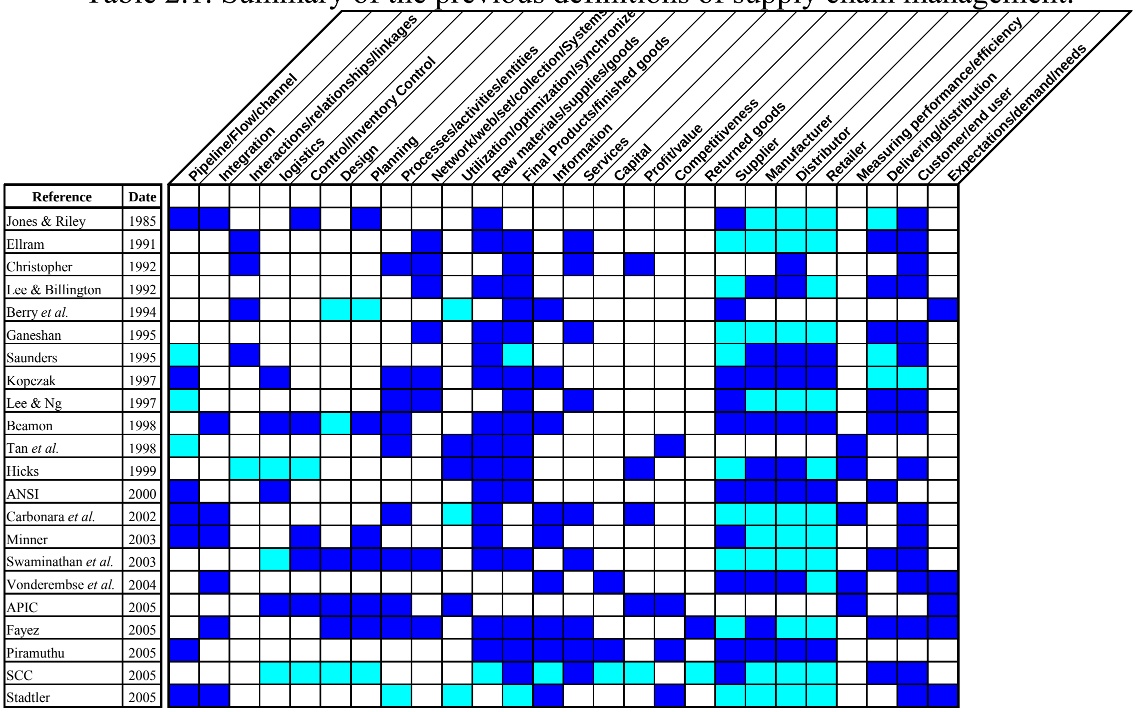
forecasting, production, distribution, fulfillment, after sales support, and end-of-life disposal" (Swaminathan and Tayur 2003).

However, perhaps a more inclusive definition is given by the SCC, which defines supply chain management as "…every effort involved in producing and delivering a final product or service, from supplier's supplier to customer's customer" (SCC 2005).

Some researchers suggest using the term supply chain management to address different problems other than the abovementioned, such as strategic, inter-organizational issues (Cox 1997), alternative organizational forms (Thorelli 1986), relationship with companies' suppliers (Krajewski *et al.* 2005; Sako 1992; Lamming 1993), reverse logistics (Beamon 1998; Mukhopadhyay and Setoputro 2005), *e*-business (Swaminathan and Tayur 2003), virtual enterprise (Lau *et al*. 2000) and radio frequency identification (Srivastava 2004).

As supply chain research has become more mature, the definitions proposed by researchers are becoming more consistent. A summary of the definitions provided by previous researchers is given in Table 2.1. Reviewing these definitions, it can be seen that supply chain management has been defined from the point of view of the problem that is being addressed. The researchers are listed in the first column of Table 2.1, while the general terms used in the researchers' definition of the supply chain are listed individually in the headings across the columns. Each row represents a supply chain definition previously provided by the researchers. The dark blue boxes in each row indicate that the terms are directly mentioned in the researchers' definition. The light blue boxes indicate that the terms are indirectly identified by the researchers in their definitions. The white boxes means that the terms are not mentioned directly or indirectly in the supply chain definition provided by each researchers.

Table 2.1. Summary of the previous definitions of supply chain management.



2.3. <u>General Review of Supply Chain Research, Management and Practice</u>

To date, there are 13 general reviews and surveys of supply chain research, supply chain management and supply chain practice (Beamon 1998; Croom *et al.* 2000; Carbonara *et al.* 2002; Huang *et al.* 2003; Minner 2003; Swaminathan and Tayur 2003; Appleqvist *et al.* 2004; Gunasekaran and Ngai 2004; Gunasekaran *et al.* 2004; Perona and Miragliotta 2004; Piramuthu 2005; Stadtler 2005; Vondrembse *et al.* 2005). These reviews provide insight and perspective about supply chain classification, types, methods of optimization, performance measurement, performance categories, *etc.* A summary of these review and survey papers is given in Table 2.2. Each row is the associated authors and the dimension of supply chain management that is reviewed. The general terms of the area reviewed are listed across the columns. The dark blue boxes in each row indicate that specific context of the researchers' review of supply chain management topics.

Table 2.2. Summary of the existing review and survey papers in supply chain research, management and practice.

Reference	SCM Topic	SC Background	SC Types	Classification	Essence & Scope of SCM	Modeling	Decision-making	Advanced Planning Systems (APS)	Performance Measurements	Performance Metrics	Automated SC configuration (ASCC	Examples/Case studies	2 Stage SC Example	3 Stage SC Example	Product Types	SC Design	Procurement & supplier selection	Visibility & Information sharing	Distribution & pricing	Customization and postponment	Sourcing	Inventory Problems	Directions for Future Research
Piramuthu (2005)	Dynamic supply chain Configuration										X	X	X	X									
Stadtler (2005)	Management & Planning				X			X															
Appleqvist *et al.(2004)*	Product & supply chain design					X	X																
Gunasekaran and Ngai (2004)	Build-to-Order supply chain			X																			
Gunasekaran *et al.* (2004)	Performance Measurement								X	X													
Perona & Miragliotta (2004)	Performance Assessment			X		X																	
Vonderembse *et al.* (2004)	Supply chain Design	X	X	X								X			X	X							
Huang *et al.* (2003)	Production Information			X		X	X		X									X					X
Minner (2003)	Multiple-supplier inventory Models			X		X															X	X	X
Swaminathan and Tayur (2003)	Models in E-Business			X			X										X	X	X	X			
Carbonara *et al.* (2002)	Supply chain within industrial districst			X								X											
Croom *et al.* (2000)	Analytical Framework			X												X							
Beamon (1998)	Design and Analysis			X	X	X	X		X														

Vondrembse *et al*. (2005) review and categorize the past work in supply chain with respect to product type and supply chain configuration, such as agile supply chains and lean supply chains. Huang *et al*. (2003) review and categorize the past research in supply chain with respect to supply chain structure, such as dyadic, network, serial, *etc*. Cooper *et al.* (1997) and Croom *et al.* (2000) review and categorize the past research in supply chain with respect to their content and area of concern, such as information flow, inventory management, planning and design, *etc.* Beamon (1998) review and categorize the past research according to their modeling approach, such as deterministic models, stochastic models, simulation models, economic models, *etc*.

2.4. Supply Chain Types and Classification

There are several types of supply chains discussed in the literature as listed below. Moreover, different terminologies are used to address the similar supply chain types. For example, agile supply chains are also referred to as adaptive and spontaneous supply chains (Anderson 2004; Vondrembse *et al.* 2004). Table 2.3 illustrates the different types of supply chains and the year their terminologies are introduced in the literature.

Table 2.3. Supply chain types and year of introduction of terminology.

Supply Chain Type	**Manufacturing Strategy**	**Year of Introduction of Supply Chain**	**Relevant References**
Supply Chain (known later as Traditional)	Make-to-Stock Make-to-Forecast Build-to-Forecast	1982	Oliver and Webber (1982)
Lean	Mass Customization	1980s – 1990s	Vondrembse *et al.* (2004); Anderson (2004) track the introduction of the terms to these periods.
Hybrid	Assemble-to-Order	1990s	
Agile/ Spontaneous/ Adaptive	Make-to-Order	1990s – 2000s	
	Engineer-to-Order		
Build-to-Order	Build-to-Order	2005	Kathawala and Wilgen (2005)

Swaminathan and Tayur (2003) and Sheikh (2003) classify supply chain management from the configuration perspective and the coordination perspective (see Figure 2.3). Several studies have urged to development of specific and generic models for designing the supply chain, optimizing supply chain operations, as well as setting performance measures for various objectives within the supply chain.

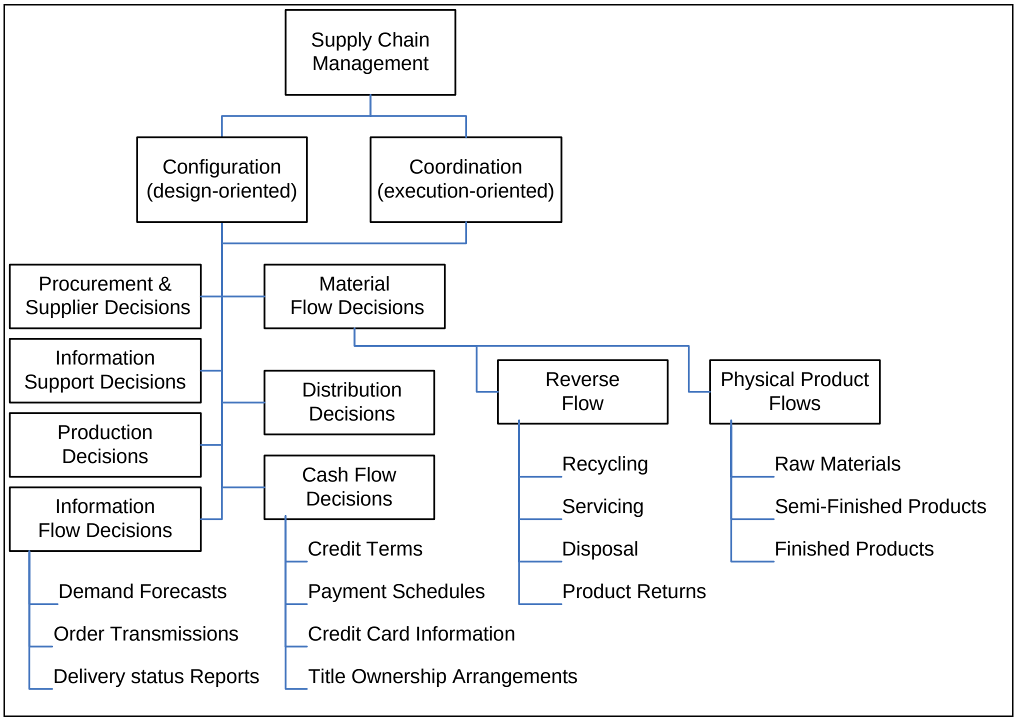


Figure 2.3. Configuration and coordination decision-making within supply chain management (adapted from Sheikh (2003)).

According to Vondrembse *et al.* (2005), the supply chain design could be classified according to product characteristics, as the authors believe that the supply chain is a function of product characteristics. Although other product types exist, Vondrembse *et al.* (2005) limit their research to three main product types: (1) *standard products*, (2) *innovative products* and (3) *hybrid products*. Standard products are traditional catalogue items, and they usually have a well-defined fixed Bill of Materials (BOM) and support a lean manufacturing strategy. They are produced based on relatively accurate forecasts, managed as make-to-stock items. Innovative products, such as computer hardware and software, cell phones, *etc.* are products that typically have short lifecycles and require more of an agile manufacturing strategy. Accurate forecasting for these types of products is slightly more challenging. These products are managed as make-to-order or build-to-order. Finally, hybrid products are standard products with agile features, *e.g.*, a customized audio and navigational system in a standard automobile, *etc.*

Vondrembse *et al.* (2005) also categorize supply chains as lean supply chains, agile supply chains and hybrid supply chains (see Table 2.4). Agile supply chains are generally associated with innovative and short lifecycle products and hybrid products. Product time-to-market and time-to-customer is critical in such supply chains due to the relatively shorter lifecycle of the product and process technologies (Vondrembse *et al.* 2005).

Table 2.4. Supply chain classification based on product type and product lifecycle (adapted from Vondrembse *et al.* (2005), Table 3, p. 12).

<table>
<tr><th>Product Type / Product Lifecycle</th><th>Standard</th><th>Innovative</th><th>Hybrid</th></tr>
<tr><td>Decline</td><td rowspan="4">Lean Supply Chain</td><td rowspan="2">Hybrid / Lean Supply Chain</td><td rowspan="4">Hybrid Supply Chain</td></tr>
<tr><td>Growth</td></tr>
<tr><td>Maturity</td><td rowspan="2">Agile Supply Chain</td></tr>
<tr><td>Introduction</td></tr>
</table>

Reeve (2002), on the other hand, classifies two supply chain types according to three product types (see Table 2.5). He considers products as: (1) *standard products,* similar to Vondrembse *et al.* (2005); (2) *configurable products*, which are either base products with configurable options, or a wholly configurable products from numerous possible combinations of options. In both cases, the components, sub-assemblies and modules are standardized for these types of products; and (3) *engineered-to-order products*, which are one-of-a-kind products that have custom-designed parts and assemblies. Figure 2.3 illustrates the material flow in a build-to-order supply chain network structure, which is the focus of this research.

Table 2.5 Supply chain type versus product type (adapted from Reeve (2002)).

Supply Chain Type	**Product Type**		
	Standard Product	**Configurable Product**	**Engineered-to-Order Product**
Make-to-Stock (BTS)/ Make-to-Forecast (MTF)/ Build-to-Forecast (BTF)	Bottled drinks, Staples, Bolts, Pencils	Automobile	N/A
Build-to-Order (BTO)	Sub-Assemblies on Kanban (*i.e.*, Color matched wheel assembly for a vehicle)	Desktop computers, Cisco network, office furniture installation	Custom power plants

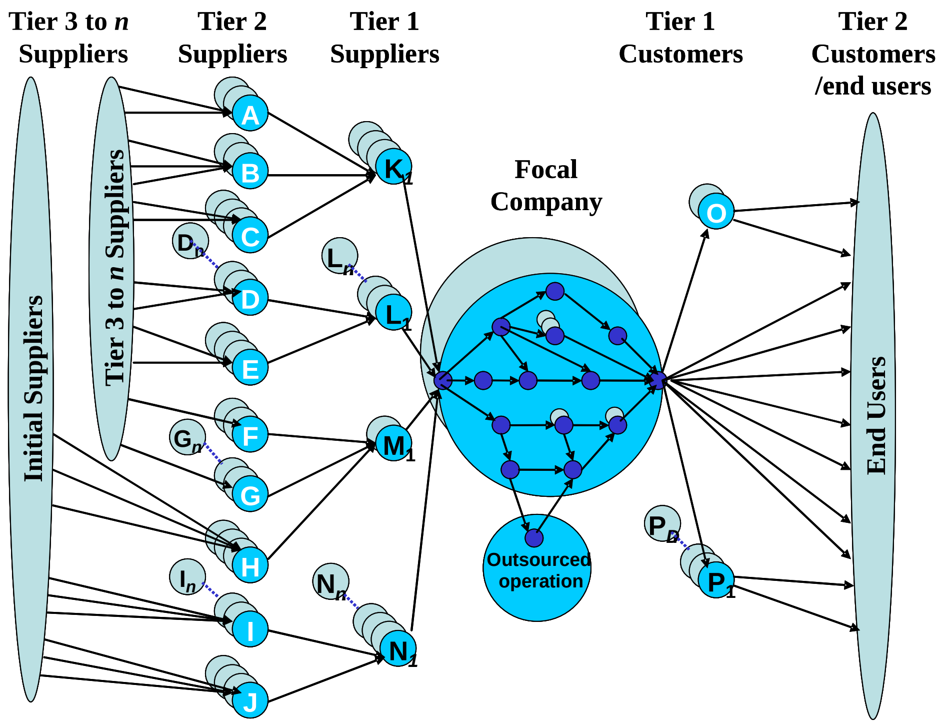


Figure 2.4. General build-to-order supply chain network structure (adapted from Lambert *et al.* (1998)).

2.5. Supply Chain Modeling Approaches

Several approaches have been used to model various aspects of the supply chain (see Beamon 1998 for a detailed summary). We extend the work of Beamon (1998) and further classify the modeling methods as shown in Table 2.6. We now discuss two of the more popular supply chain modeling approaches that have been used throughout industry – the Supply Chain Operations Reference model and the Global Supply Chain Forum framework.

Table 2.6. Supply chain modeling approaches and partial list of references.

Supply Chain Modeling Methods			
Math-based / Exact	Mathematical Programming	Linear Programming	Spitter *et al.* (2005); Hicks (1999); D'Amours *et al.* (1999)
		Integer Programming	Hwand (2002); Alonso-Ayuoso *et al.* (2003); Beamon and Fernandes (2004)
		Mixed Integer Programming	Hicks (1999); Truong and Azadivar (2003); Dudek and Stadtler (2005); Lakhal *et al.* (2000); Tsiakis *et al.* (2001); Cakravastia *et al.* (2002)
		Non-linear	Chen and Lee (2004)
	Network Modeling	Deterministic Analytical	Baiman *et al.* (2001); Cohen and Agrawal (1999)
		Stochastic Analytical	Hicks (1999); Gellouli and Chatelet (2001); de Kok *et al.* (2005); Piramuth (2005); Umeda and Jones (1998); Nagurney *et al.* (2005); Santoso *et al.* (2005); Nagurney *et al.* (2003)
	Others	Analytical Mathematical Models	Aviv (2001); Baiman *et al.* (2001); Choi *et al.* (2004); Tsay and Lovejoy (1999); Guiffrida and Nagi (in press); Mukhopadhyay and Setoputro (2005); Chen *et al.* (2000); Das and Abdel-Malek (2003); Kim *et al.* (2002)
		Dynamic Programming	Wend and Parlar (2005)
		Optimization	Savaskan (2004); Schultz *et al.* (2005)
Heuristic / AI-based/Search	Simulation	System Dynamics	Lau *et al.* (2001); Fiala (2005)
		Parallel & Distributed	Terzi and Cavalieri (2004)
		Network Simulation	Hicks (1999); Truong and Azadivar (2003);Gellouli and Chatelet (2001); Tah (2005)
		Web-based	Lau *et al.* (2002); Lau *et al.* (2001)
		Single Path/Multi Process	Gellouli and Chatelet (2001); Aslanertick (2005); Mohebbi and Choobineh (2005); Nair and Closs (in press); Abdel-Malek (in press);
		Object Oriented/ UML	Lau *et al.* (2002); Lau *et al.* (2001);
	Multi-agent systems		Lau *et al.* (2002); Lou *et al.* (2004); Kaihara (2003); Liang and Huang (in press); Wagner *et al.* (2003); Chan and Chan (2004)
	Genetic Algorithms		Joines *et al.* (2002); Truong and Azadivar (2003); Gellouli and Chatelet (2001); Liang and Huang (in press); Berning *et al.* (2004); Syarif *et al.* (2002)
	Neural Networks		Taudes *et al* (2002)
	Fuzzy Logic		Geneste *et al.* (2003); Chen and Lee (2004)
Qualitative/ Mapping	Mapping	SCOR	Wang *et al.* (2004); Stefansson and Holmqvist (2005); Bolstroff (2001); White and Barnette (2004); Pundoor and herrmann (2004); Bolstroff (2005); Huang *et al* .(2005)
		e-SCOR	Barnette and Miller (2000); Industry direction (2001)
		e-business	Manthou *et al.* (2004)
	Qualitative	Six-Sigma	Pande, (2002)
Other	Economic	Cost/ financial measures	Guiffrida and Nagi (in press); Ertek and Griffin (2002); Kaihara (2003)
		Stochastic Inventory Model	Ryu and Lee (2003); Hua *et al.* (in press); Cachon (2004); Kouvelis and Milner (2002)
	Conceptual	Differentiation	Wong *et al.* (in press)
		Theoretical representation	Penora and Miragliotta (2004); Carbonara *et al.* (2002); Kulp *et al.* (2004); Themistocleous *et al.* (2004); van Donk and van der Vaart (2005); Andersen and Christensen (2005)
		Survey/Questionnaire	Krajewski *et al* (2005); Bhatnagar and Sohal (2005); Jain *et al.* (2002); Arend and Wisner (2005); Zhang *et al.* (2003)
	Decision Making	Sensitivity Analysis	Mukhopadhyay and Setoputro (2005); Ryu and Lee (2003)
		AHP	Wang *et al.* (2004)

2.5.1. Supply Chain Modeling in Industry

To date, there are two fairly well-documented and integrated supply chain frameworks that are implemented in practice and applied globally by many supply chain entities for supply chain modeling and management. These two frameworks are the Supply Chain Operations Reference model and Global Supply Chain Forum framework.

2.5.1.1. <u>The Supply Chain Operations Reference Model</u>

The Supply Chain Operations Reference (SCOR) model, which was introduced by the Supply Chain Council in 1996, is a process-based model that captures the Council's agreed representation of the supply chain management and charts processes commonly associated with the logistics of manufacturing products. SCOR has structured performance metrics to help measure the performance of an organization's supply chain relative to peers and leaders in class (SCC 2005). Figure 2.5 illustrates a high-level representation of the SCOR model processes and categories. The SCOR model classifies the supply chain into five major operations: Plan, Source, Make, Deliver and Return. The supply chain entities or tiers of supply chain entities are integrated through a set of activities and operations with respect to the abovementioned operations.

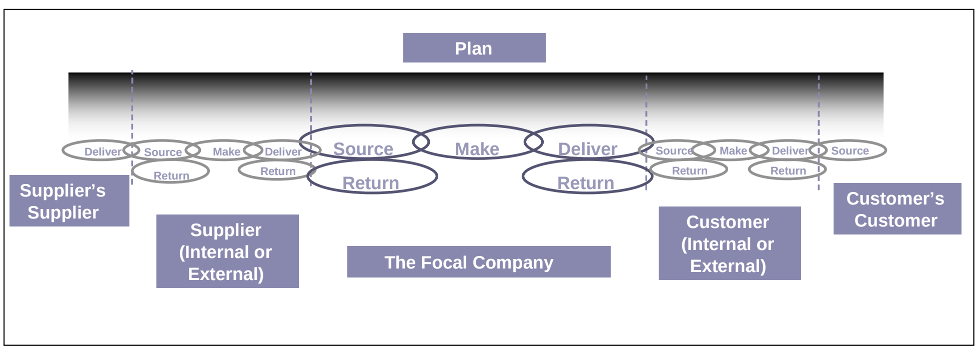


Figure 2.5. Global representation of the SCOR model processes and categories (obtained from SCC (2005)).

There are four levels of analysis in SCOR modeling, which are as shown in Figure 2.6. Level 1 is the process analysis. Level 2 is a lower-level representation of the process elements analysis. Level 3 is the analysis of the tasks within the process elements. Finally, Level 4 includes the analysis within the process element tasks. Level 4 is specific to each supply chain organization and hence it is beyond the generic representation of SCOR modeling. Figure 2.7 provides further illustration of the SCOR levels of process details.

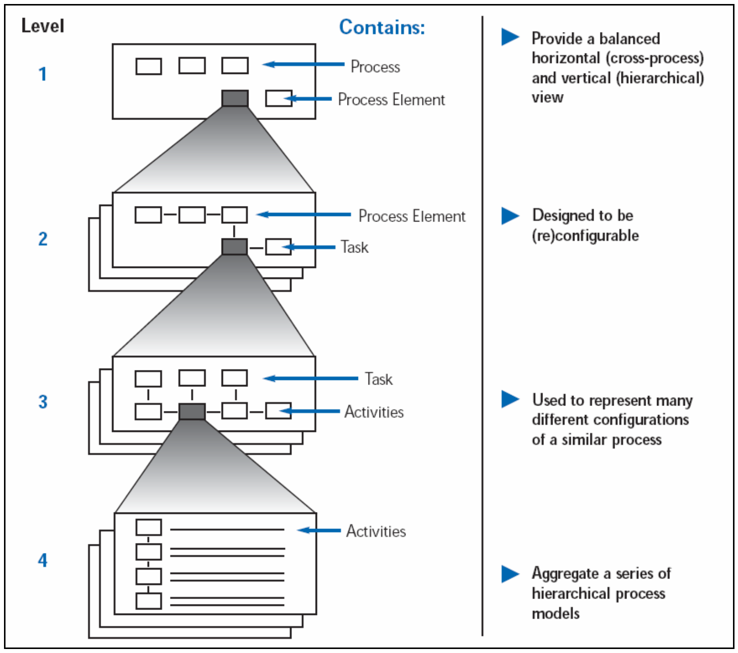


Figure 2.6. The general levels of analysis of the SCOR model (obtained from SCC (2005)).

Simchi-Levi *et al.* (2004) suggest that the SCOR modeling approach has the potential of becoming an industry standard as it is considered one of the more successful attempts in mapping and modeling the overall supply chain (SCC 2005). The model classifies supply chains into four classes according to product types: (1) make-to-stock, (2) make-to-order, (3) engineer-to-order and (4) retail business.

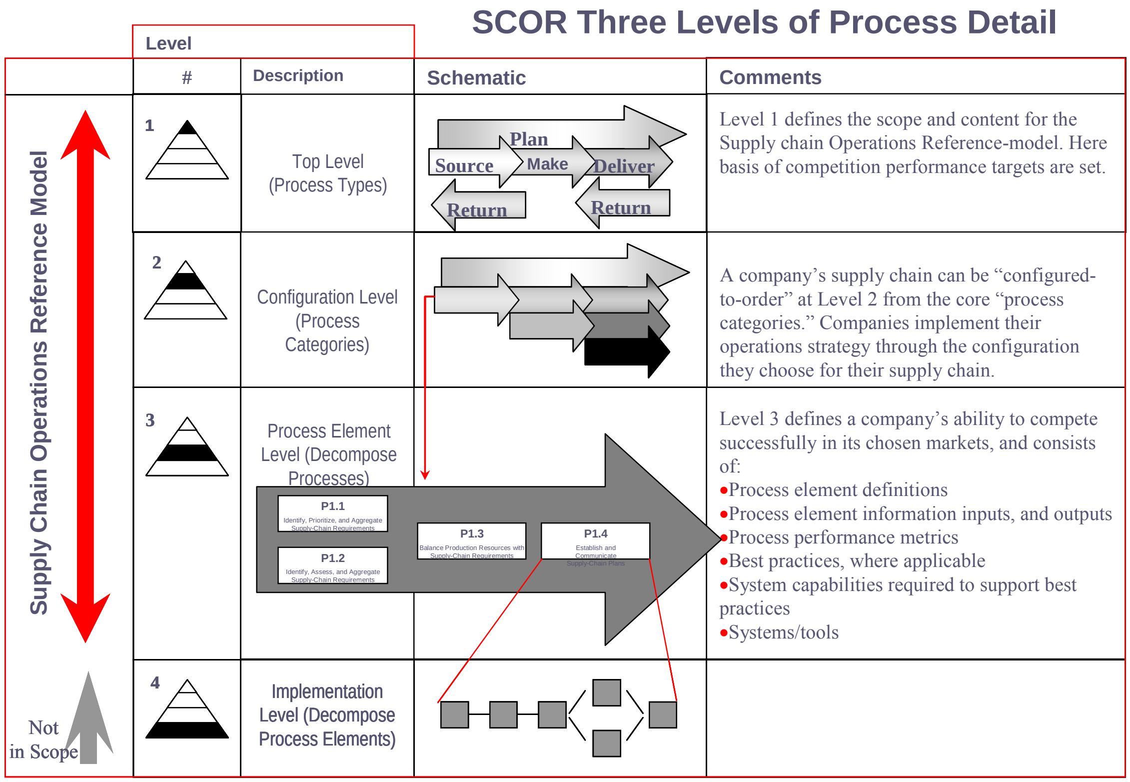


Figure 2.7. Illustration of SCOR levels of analysis (obtained from SCC (2005)).

2.5.1.2. The Global Supply Chain Forum Framework

The Global Supply Chain Forum (GSCF) framework is proposed by Dr. Douglas Lambert and a team of researchers in the Fisher School of Business at The Ohio State University. The GSCF framework is a process-based representation of the supply chain that is considered an alternative to the SCOR model. The GSCF framework includes eight supply chain management processes, which are: Customer Relationship Management, Customer Service Management, Demand Management, Order Fulfillment, Manufacturing Flow Management, Supplier Relationship Management, Product Development and Commercialization, and Returns Management. As suggested by Lambert (2005), Customer Relationship Management and Supplier Relationship

Management form the critical links of the supply chain, while the six processes are synchronized through them. Each of the eight processes is cross-functional and cross-firm, and can be broken down into a sequence of strategic sub-processes, and a sequence of operational sub-processes, and each sub-process is described by a set of activities (Lambert 2005). Figure 2.8 shows a global representation of the GSCF framework illustrating the integration of the various management aspects of supply chains, the directions of flow of business processes along the supply chain, and the different components within a manufacturing supply chain. The GSCF framework analyzes the various supply chain business processes with respect to the global flow of information, cash flows, and products flow between supply chain entities with respect to profit and loss opportunities within each of the eight supply chain business processes (Lambert *et al.* 1998). Table 2.7 lists and classifies the differences between the SCOR model and the GSCF framework.

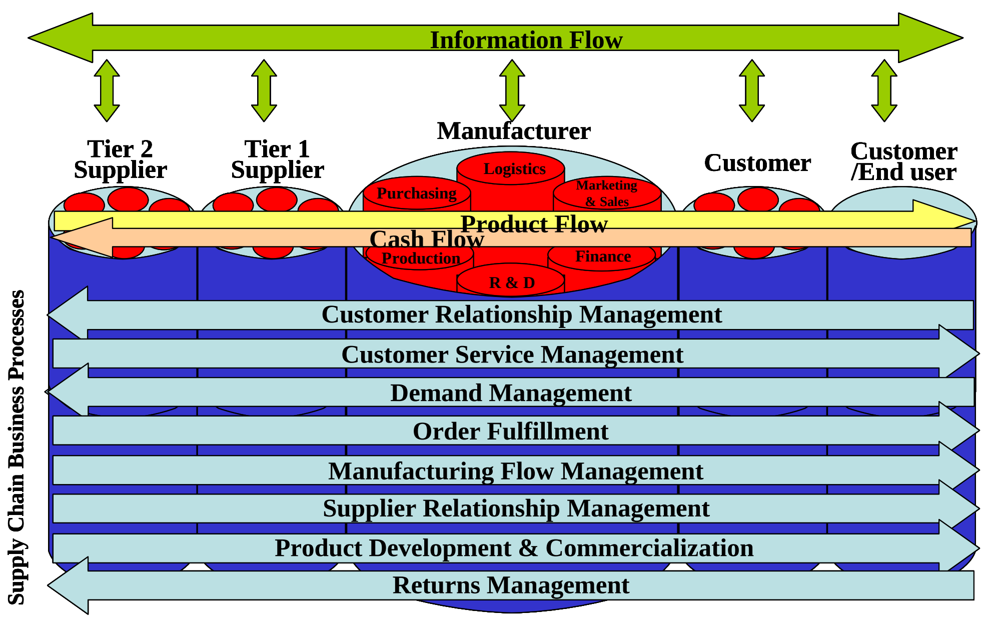


Figure 2.8. The GSCF framework and shows the integration of the processes across the supply chain (adapted from Cooper *et al.* (1997) and Lambert *et al.* (1998)).

Table 2.7. Comparison between the SCOR model and the GSCF framework (summarized from SCC (2005) and Lambert (2005)).

	SCOR Model	**GSCF Framework**
Focus	Achieving transactional efficiency within the realm of purchasing, manufacturing and distribution	Relationship management and integrating all activities within the firm and with key members of the supply chain
	Involves functions that are more easily integrated	More strategic and focuses on increasing long-term shareholder value through closer cross-functional relationships with supply chain key members
	Provides a tactical approach that address symptoms through tactics	Provides a strategic approach to address supply chain management processes incorporating the knowledge, expertise and objectives of all functions.
Strategic Alignment	Processes are developed based on the operations strategy only, considering neither corporate strategy nor alignment with other functional strategies	Each process is aligned with corporate strategy and appropriate functional strategies either directly or indirectly through customer relationship and supplier relationship management processes.
Breadth of Activities	Include only activities related to forward and backward flow of products, and planning required to manage these flows	Very broad in scope, including product development, demand generation, relationship management and returns avoidance
Cross-Functional Involvement	Pursued primarily within three functions: Logistics, Production and Purchasing	Touches all aspects of the business and includes representation from all incumbent functions, including Marketing, Sales, Finance, *etc.*
Process and Performance Benchmarking	Provides a set of benchmarking tools that includes performance benchmarking and process benchmarking "best practice analysis"	Starts with the objectives and develop strategies and tactics to meet them in a rapidly changing business environment
Value Creation	The drivers of value creation are focused on cost reductions and improvements in asset utilization	Operational measures are tied to the firm's Economic Value Added (EVA) and to profitability reports for customers and suppliers
	Cost reductions will yield large savings for supply chains that experience lower levels of efficiency	Considers revenue generation as well as cost reduction, which is essential for long-term financial success
Advantages and Strengths	Possibility of identifying areas of improvement and "quick-hits" in cost reduction and asset efficiency	More useful for businesses that consider the capability to identify, build and maintain business relationships to be a competitive advantage
	SCOR is easier to implement	Include all functions and processes included in supply chain
Disadvantages and Limitations	Does not address every business process or activity, *i.e.*, neither of Sales, Marketing, Research & Development, Product Development processes, nor Returns avoidance opportunities are included. No critical inputs from non-included activities are considered	The eight supply chain management processes are all interrelated and have to start at the same time making it very difficult to start small. Also, It is difficult to manage the interfaces between firms in the supply chain when significant changes are taking place within the focal company

2.6. Variability in Supply Chain Management

There is a distinction in the literature between variability and uncertainty. Variability refers to controllable and uncontrollable changes that are driven by factors in a system process or activity. *Controlled variability* is that for which one can manage or control the driving factors and for which one can proactively plan. *Uncontrollable variability* is that for which the sources of the variation cannot be managed and changed in the short-term. A distinction is made between uncontrollable variability that is known and uncontrollable variability that is unknown due to uncertainty (or randomness).

A supply chain is stochastic in nature as uncertainty is associated with the supply chain from both the supply and demand perspectives (Weng and Parlar 2005; Krajewski *et al.* 2005; Sharma and Laplaca 2005; Gunasekaran and Ngai 2005; Christensen *et al*. 2005; Mukhopadhyay and Setoputro 2005). Demand uncertainty often arises due to the difficulty in estimating the customer demand over a certain planning horizon. Supply uncertainty is caused by the difficulty in assessing types and quantities of various product parts and components to store as a buffer stock as well as resource capacity in supplying or manufacturing these parts and components (Gunasekaran and Ngai 2005).

In any supply chain, the unexpected variation in activity time could be due to unexpected changes in resource capacity along the supply chain, stochastic durations of delivery, unreliable material handling, variable material and product quality, fluctuating raw material costs, and variation due to human-based activities (such as experience, person-to-person variation, shift, location, *etc.*). These unexpected changes typically would occur during the execution of supply chain operations potentially delaying the manufacture of products and delivery of orders to customers. Hence, excessive variation can drastically decrease the expected associated profit of the firm (Chen and Lee 2004).

The degradation in performance due to the presence of variability in the supply chain is the *bullwhip effect*. The bullwhip effect has been studied extensively in the supply chain literature. Numerous researchers study this phenomenon and demonstrate its existence and its negative effects on supply chain performance (*e.g.*, Alwan *et al.* 2003; Fiala *et al.* 2005; de Kok *et al.* 2005; Metters 1996; Lee *et al.* 1997a; Lee *et al.* 1997b; Chen *et al.* 2000; Simchi-Levi *et al.* 2004). The variability that causes the bullwhip effect usually originates at the point of external customer demand and increases upstream towards the suppliers of raw materials, individual parts, components and subassemblies. This can lead to insufficient or excessive inventories, capacities and costs at various stages in the supply chain. The distortion of demand information is typically the root cause of the bullwhip effect, and this demand information becomes increasingly distorted as the information moves upstream in the supply chain (Alwan *et al.* 2003). Figure 2.9 illustrates the origination and progression of the bullwhip effect in a traditional supply chain. Notice that there is a lead time between order placement and order delivery fulfillment at every stage of the supply chain. Information flows between the different stages in the supply chain and any variation in the information being passed between these stages will contribute to the bullwhip effect.

There are situations where the bullwhip effect originates due to variation from other points in the supply chain. For instance, fluctuations in internal orders cause variation in lead times associated with satisfying those internal orders. Also, internal forecasting due to no or inaccurate information sharing is a major cause of variation along the supply chain (Chen *et al.* 2000; de kok *et al.* 2005; Fiala 2005; Simchi-Levi *et al.* 2004). Table 2.8 lists several published works in supply chain dynamics, variability, and demand uncertainty.

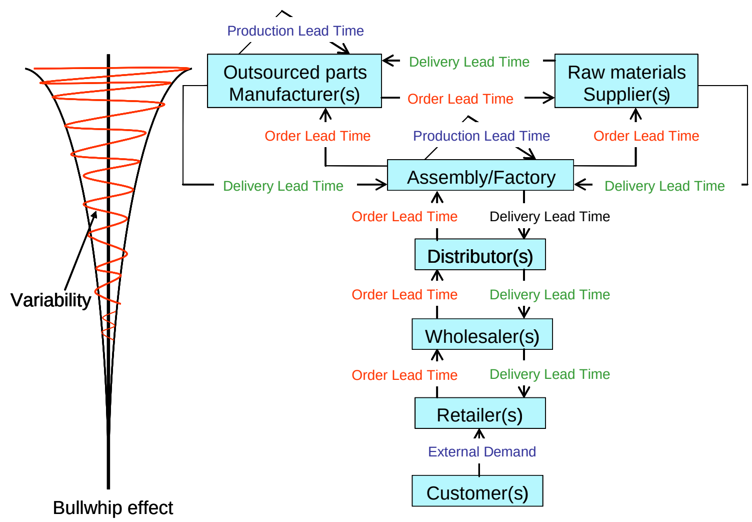


Figure 2.9. The influence of lead time variation on the bullwhip effect in traditional supply chains. (adapted from Simchi-Levi *et al.* (2004)).

Table 2.8. Partial list of published works that consider supply chain dynamics, variability and uncertainty.

Author(s)	Literature Review	Variability			Bull-whip Effect	Demand Forecast Uncertainty	Information Flow	Propose a Model	Decision-Making	Supply Chain Performance	Network Modeling	Simulation	Optimization	BOSC
		Demand/ Order Quantity	Supply / Components Cost	Order Lead Time										
Alonso-Ayuoso *et al,* (2003)		✓	✓					✓	✓	✓				
Alwan *et al,* (2003)					✓	✓		✓						
Cachon, (2004)		✓	✓					✓		✓				✓
Chen and Lee, (2004)		✓							✓	✓	✓		✓	
Chen *et al,* (2000)				✓	✓	✓	✓	✓						
Das and Abdel-Malek, (2003)		✓			✓			✓		✓	✓			
de Kok *et al,* (2005)		✓		✓	✓	✓		✓			✓			
Fiala, (2005)					✓		✓	✓	✓	✓	✓	✓	✓	
Grabot and Letouzey, (2003)				✓		✓		✓						
Guiffrida and Nagi, (2005)				✓				✓		✓				
Hua *et al,* (in press)		✓	✓											✓
Kaihara, (2003)		✓	✓											
Kouvelis and Milner, (2002)		✓	✓					✓						
Krajewski *et al,* (2005)		✓	✓							✓				✓
Lau *et al,* (2002)		✓	✓		✓		✓					✓		
Nagurney *et al,* (2003)		✓	✓					✓			✓			
Nagurney *et al,* (2005)		✓	✓					✓					✓	
Piramuthu, (2005)				✓			✓			✓				
Swaminathan *et al,* (1998)		✓					✓	✓		✓	✓	✓	✓	
Santoso *et al,* (2005)			✓					✓		✓	✓			
Tsay and Lovejoy, (1999)		✓			✓	✓		✓		✓				
Tsiaskis *et al,* (2001)		✓						✓	✓	✓	✓		✓	
van Donk & van der Vaart, (2005)		✓		✓										
Wagner *et al,* (2003)								✓		✓				✓
Wong *et al,* (in press)		✓				✓								

2.7. Performance Measurement in Supply Chain Management

Measuring the performance of the supply chain is very essential for better management and control of all supply chain activities. Supply chain performance measures have been described according to four dimensions: the domain, the category, and the facing (Swaminathan *et al*. 1998; SCC 2005).

The domains of most supply chain performance measures are either *local* or *global*. Local performance measures are intra-organizational supply chain performance measures, where the majority of supply chain members belong to the same organization. Global performance measures are inter-organizational supply chain performance measures, where the majority of supply chain members belong to separate organizations. The organizations then integrate to form a supply chain for certain products (or services) (Swaminathan *et al*. 1998).

Measures of supply chain performance are categorized as either *qualitative* or *quantitative*. Qualitative performance measures are related to customer satisfaction, flow of material along the supply chain, the level of integration of information within the supply chain, and effective risk management. Quantitative performance measures are related to profit, cost, fill rate, customer response time, supplier reliability, manufacturing/delivery lead time and other measurable quantities (Swaminathan *et al*. 1998).

The Supply Chain Council classifies supply chain performance in its performance metrics of its SCOR model version 7.0 (SCOR V7.0) according to their facing. The five general metrics are shown in Figure 2.10. In the context of Customer Relationship Management, customer-facing is "…anything that the customer of a business deals with directly" (TechTarget 2006). In supply chains, the customers of a business interface directly with the supply chain's reliability, flexibility and responsiveness. On the other hand, supply chain cost and asset management are internal-facing as they are considered internal matters to the supply chain organization (*i.e.,* focal company) and not exposed to customers. However, the price of the product or service would still be customer-facing.

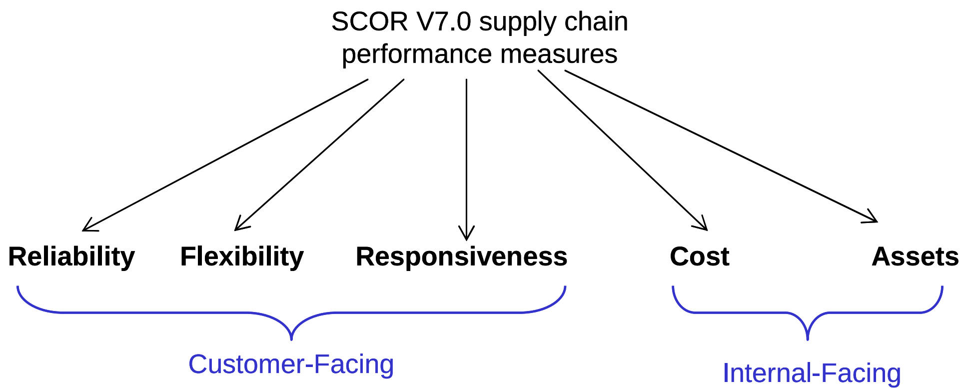


Figure 2.10. Supply Chain Council SCOR V7.0 model supply chain performance measures.

The majority of the past research on supply chain performance measures emphasizes the use of integrated measures and evaluating overall supply chain global performance rather than evaluating the local performance of individual supply chain members (Schmitz and Platts 2004). Other researchers have shown that local performance measures are inappropriate measures to achieve the supply chain network overall performance (Schmitz and Platts 2004; Choi *et al.* 2004). It is appropriate not only to evaluate performance on micro-level but also evaluate performance on the macro-level due the butterfly effect one location has on other locations within the supply chain.

Simchi-Levi *et al.* (2004) suggest that using the SCOR model performance metrics is an effective method for evaluating supply chains within the same industry. The SCOR model considers the following performance measures: (1) cost, (2) flexibility, (3) reliability, (4) asset management and (5) responsiveness. The SCOR modeling approach refers to the five general performance measures as attributes, and for the sake of this discussion, we use the SCOR and refer to performance measures as performance attributes.

The general performance attributes used by the SCOR model performance metrics will be considered in this research investigation. SCOR evaluates the five performance attributes in terms of some measured aspects of a supply chain as shown in Level 1 metric of Table 2.9.

Table 2.9. SCOR Level 1 performance metrics (obtained from SCC (2005)).

Level 1 Metrics	Performance Attributes				
	Customer-Facing			Internal-Facing	
	Reliabilty	Responsiveness	Flexibility	Cost	Assets
Perfect Order Fulfillment	✔				
Order Fulfillment Cycle Time		✔			
Upside Supply Chain Flexibility			✔		
Upside Supply Chain Adaptability			✔		
Downside Supply Chain Adaptability			✔		
Supply Chain Management Cost				✔	
Cost of Goods Sold				✔	
Cash-to-Cash Cycle Time					✔
Return on Supply Chain Fixed Assets					✔

SCOR includes metrics for measuring various aspects related to every performance attribute. It also provides a set of benchmarking tools that includes performance benchmarking and process benchmarking "best practice analysis." Once the metric is calculated for every performance aspect, the value is compared to the performance benchmarks. If values are less than the performance benchmark, then process benchmarks become useful to consider for system improvement. Performance attributes in SCOR can be classified under three different aspects in Level 2, *i.e.*, cost-related (monetary values), time-related (durations), and product quantities (product units) as shown in Table 2.10.

Table 2.10. Summary of SCOR performance aspects and related measuring units (SCC (2005).

General Performance Measures	Specific Performance Metric	Value ($)	Duration (Time)	Percentage (%)	Units of Product
Reliability	Perfect Order Fulfillment			Orders Meeting Delivery	
Responsiveness	Order Fulfillment Cycle Time		Average Actual Cycle Time		
Flexibility	Upside Supply Chain Flexibility (per 20% unplanned increase in quantities delivered)		Days		
	Upside Supply Chain Adaptability (per 30 days)			Maximum Increase in Quantities Delivered	
	Downside Supply Chain adaptability (per 30 days)				Reduction in quantities ordered
Cost	Supply Chain Management Cost	Sum of direct & indirect expenses			
	Cost of Goods Sold	Sum of material + production			
Asset Management	Cash-to-Cash Cycle Time		Investment flow back duration		
	Return of Supply Chain Fixed Assets			(Supply Chain Revenue – COGS – SCM costs)/Supply Chain Fixed Assets	

Table 2.11 through Table 2.15 summarize the five performance attributes and associated Level 1 metrics. In addition, previous work that considers supply chain performance measures similar to those used by the SCOR model is provided.

Table 2.11. Definition of the SCOR model cost Level 1 performance metric.

Performance Measure:	**Cost**
Control Level	Minimize

Author(s)	Domain	Definition	Aspects Measured: SCM cost	Aspects Measured: Costs of goods sold		
SCC, (2005): SCOR Model V7.0	Global SC	The costs associated with operating the supply chain	✓	✓		

Table 2.12. Definition of the SCOR model flexibility Level 1 performance metric.

			Aspects Measured			
Performance Measure:	**Reliability**					
Control Level	Maximize					
Author(s)	Domain	Definition	**Perfect order fulfillment**			
SCC, (2005): SCOR Model V7.0	Global SC	The performance of the supply chain in delivering: the correct product, to the correct place, at the correct time, in the correct condition and packaging, in the correct quantity, with the correct documentation, to the correct customer.	✓			

Table 2.13. Definition of the SCOR model reliability Level 1 performance metric.

			Aspects Measured			
Performance Measure:	**Reliability**					
Control Level	Maximize					
Author(s)	Domain	Definition	**Perfect order fulfillment**			
SCC (2005): SCOR Model V7.0	Global SC	The performance of the supply chain in delivering: the correct product, to the correct place, at the correct time, in the correct condition and packaging, in the correct quantity, with the correct documentation, to the correct customer.	✓			

Table 2.14. Definition of the SCOR model asset management Level 1 performance metric.

			Aspects Measured			
Performance Measure:	**Asset Management**					
Control Level	Maximize					
Author(s)	Domain	Definition	**Cash-to-cash cycle time**	**Return on SC fixed assets**		
SCC (2005): SCOR Model V7.0	Global SC	The effectiveness of an organization in managing assets to support demand satisfaction. This includes the management of all assets: fixed and working capital.	✓	✓		

Table 2.15. Definition of the SCOR model responsiveness Level 1 performance metric.

			Aspects Measured			
Performance Measure:	**Responsiveness**					
Control Level	Maximize					
Author(s)	Domain	Definition	**Order fulfillment cycle time**	**Inventory levels**	**Lead times**	**Capacities**
SCC, (2005): SCOR Model V7.0	Global SC	The speed at which the supply chain provides products to the customer.	✓			
Holweg and pil, (2005)	Supplier performance	Viewed in light of inventory levels. If supplier and manufacturer are coretly alligned, supplier should be able to use smaller production batches and deliver product more frequently.		✓		

Previous work that considers supply chain performance measures similar to those used by the SCOR model is summarized in Table 2.16.

Table 2.16. Partial list of published works that consider supply chain performance measures.

Author(s)	Literature Review	Risk minimization	Cost	Profit	Responsiveness	Flexibility	Reliability	External/ Internal Failure	Efficiency (= profit /max. profit)	Effectiveness	Fill rate	Stock out rate	Local	Global	Propose a Model	Decision-Making	Network Modeling	Simulation	Optimization	BOSC
		Performance Measure											Domain							
Alonso-Ayuoso *et al,* (2003)			✓	✓										✓	✓	✓				
Aviv, (2001)			✓										✓							
Baiman e*t al,* (2001)								✓	✓				✓							
Cachon, (2004)		✓	✓	✓					✓						✓					✓
Chen and Lee, (2004)			✓	✓												✓	✓		✓	
Choi *et al,* (2004)											✓	✓								
Das and Abdel-Malek, (2003)						✓									✓		✓			
Guiffrida and Nagi, (2005)			✓										✓		✓					
Gunasekaran *et al,* (2004)	✓		✓			✓				✓				✓						
Holweg and pil, (2005)					✓								✓							
Krajewski *et al,* (2005)						✓								✓						✓
Nagurney *et al,* (2005)		✓		✓										✓	✓		✓		✓	
Perona and Miragliotta, (2004)									✓	✓				✓						
Piramuthu, (2005)				✓										✓						
Randall and Ulrich, (2001)			✓										✓							
SCC, (2005)			✓	✓	✓	✓	✓													
Schmitz and Platts, (2004)	✓		✓	✓	✓	✓	✓						✓	✓						
Semchi-Levi *et al,* (2004)	✓		✓	✓	✓	✓	✓						✓	✓						
Santoso *et al,* (2005)		✓	✓												✓		✓			
Tsay and Lovejoy, (1999)						✓								✓	✓					
Tsiaskis *et al,* (2001)			✓											✓	✓	✓	✓		✓	
Wagner *et al,* (2003)					✓	✓								✓	✓					✓
Wong *et al,* (in press)					✓									✓						
Zhang *et al,* (2003)						✓							✓							

2.8. <u>The Emergence of the Build-to-Order Supply Chain Management</u>

The build-to-order manufacturing strategy was initially introduced by the Association for Manufacturing Excellence (AME) in 1998 (Anderson 2004). The emergence of build-to-order supply chains is primarily due to the long duration of inventoried finished products downstream in the supply chains, and the oft-excessive buffered inventory. For example, the excess buffered inventory in US automotive industry is about US \$80 billion worth of inventory on 20,000 U.S. dealer lots, while only about 20% of the customers acquire the exact vehicle they desire. The increasing desire of firms to increase flexibility and responsiveness of the supply chain to become more adaptive to changes in customer demand has been a significant influence. Industry experts predict that, during the next three to seven years, there will be an automotive manufacturing revolution, where current automotive manufacturers will outsource nearly everything except for design, marketing, and the customer relationship to their suppliers (Build-To-Order 2004). The Economist (2002) echoes this point by stating that:

> "...[OEM's] will disappear. In their place will be vehicle brand owners. They will do only the core tasks of designing, engineering and marketing vehicles. Everything else, including even final assembly, may be done by the parts suppliers" (The Economist, 2002).

Recently, there is a shift in large scale and major industries, including the automotive industry, to wards applying the BOSC strategies. According to Anderson (2003), Figure 2.11 illustrates the general structure of a build-to-order supply chain.

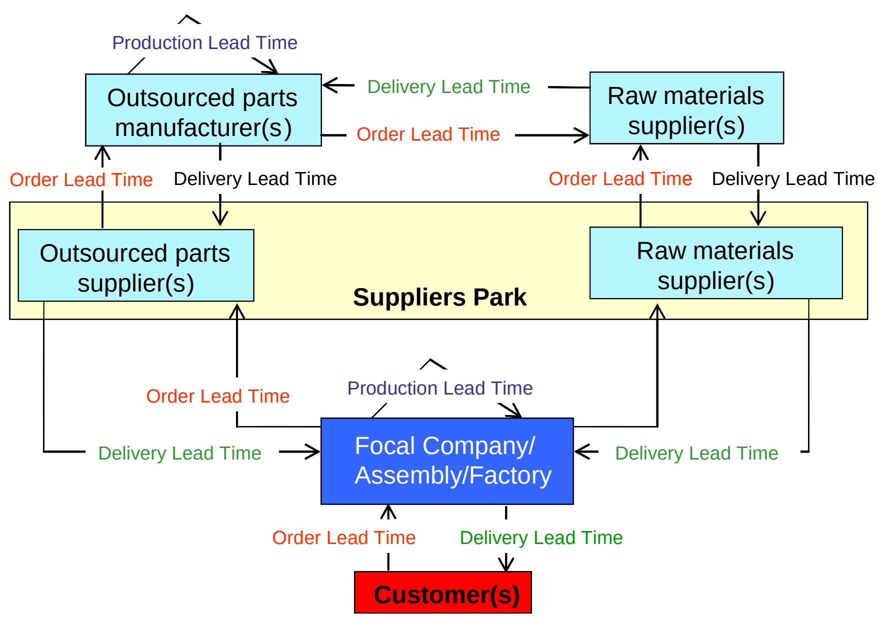


Figure 2.11. Typical structure of a build-to-order supply chain.

In build-to-order supply chains, manufacturers rely on supplier parks that house the suppliers and co-locate them in close proximity to assembly facilities. Such co-location suits the build-to-order production strategy (Holweg and Pil 2005). Utilizing supplier parks supports the inclination of the focal company to outsource various responsibilities to its suppliers and subcontractors and achieves a primary advantage of reducing the large investments tied to fixed assets by shifting the inventories to the supplier (Sako 2005). Furthermore, by maintaining supplier parks and selling directly to the customers, manufacturers can then control the order variability along the supply chain and potentially reduce the bullwhip effect. This approach also resolves the variability associated with high product variety. This reduction in variability frees management capacity to give attention to the uncertainty associated with manufacturing agile products. Even in the highly-standardized products such as automobiles, the shift from mass production to build-to-order is starting to take place. (Howard *et al.* 2005; Holweg and Pil 2005; Sako 2005). To date, there are approximately 35 supplier parks utilized in Europe in an attempt to help shift supply chain design configurations to build-to-order configurations (Sako 2005).

The second advantage of applying build-to-order philosophy is the elimination of the wholesalers and retailers, which allows new agile products with short lifecycles to be introduced rapidly to the market and shipped directly to customers without the need of depleting the inventories of the old product inventories at the wholesalers and retailers prior to production of the new product. This allows the focal company to gain larger marketshare and sell its new products while achieving high profits at the introduction and growth phase of the newly-introduced product. Hence, applying build-to-order strategy can facilitate more responsiveness, higher profits, and more cost reductions. Table 2.17 is a listing of past work that considers BOSCs, which is limited and fractured at best.

Table 2.17. Partial list of published works that consider build-to-order supply chain systems.

Author(s)	Literature Review	Variability	Uncertainty	Schedule Changes	Relationship				Simulation	Performance Measurement	Market performance	JIT Strategy	BTO Strategy
					Supplier/ Manufacturer	Manufacturer/ Retailer	Manufacturer / Customer						
Christensen *et al,* (2005)					✓		✓			✓	✓	✓	✓
Gunasekaran and Ngai, (2005)	✓												✓
Holweg and Pil, (2005)										✓			✓
Howard *et al,* (2005)					✓		✓			✓			✓
Hua *et al,* (in press)			✓			✓							✓
Kathawala and Wilgen, (2005)	✓				✓							✓	✓
Krajewski *et al,* (2005)			✓	✓	✓					✓			✓
Moses and Gruenwald, (2005)													✓
Mukhopadhyay and Setoputro, (2005)													✓
Sharma and LaPlace, (2005)											✓		✓
Sheikh, (2003)													✓
Wagner *et al,* (2002)		✓								✓			✓
Weng and Parlar, (2005)													✓

2.9. <u>Discussion of Research Gap</u>

In their recent study of supplier's logistics performance measurement, Schmitz and Platt (2004) state that:

> "…to our knowledge, there is no research on any real application of an integrated performance measurement system for supply chain management. Rather, this area is identified as a gap in the literature" (Schmitz and Platt 2004).

This conclusion is also drawn by Lambert *et al.* (1998). However, the assumption of these researchers still holds. That is, no one to date has successfully implemented a global integrated multi-performance measurement system for supply chains, which takes into consideration all the major attributes simultaneously such as asset management, responsiveness, flexibility, cost and reliability. The major limitation on supply chain management efforts is due to the fact that the global performance of supply chain relies on the joint performance of all members, which are often managed independently and have conflicting objectives (Schmitz *et al.* 2004). This limitation has a greater impact on BOSCs due to their very nature resulting in the need for higher levels of cooperation and integration.

BOSCs face high uncertainty due to individual customer's demand and product returns as well as the short lifecycle of the products with which they are associated. Besides the importance of measuring the performance of the BOSC in terms of asset management and overall costs, other measures of performance are required to be controlled and planned during the design and operation phases of BOSCs. During the strategic design phase, measures of performance such as responsiveness, reliability, overall costs and assets should be controlled with the aid of sensitivity analysis to identify a set of possible dynamic configurations that would achieve these requirements. Moreover, in the operational phase, the performance of the BOSC should be managed to become very responsive to demand uncertainty and should be very flexible in the presence of process variability. Gunasekaran and Ngai (2005) claim that:

> "…(a) there is a lack of adequate research on the design and control of BOSC, (b) there is a need for further research on the implementation of

BOSC…(e) the trade-off between responsiveness and the cost of logistics needs further study…”

Based on our extensive review of the past research, the statement by Gunasekaran and Ngai (2005) strongly supports our claim that modeling a global integrated multi-performance measuring system in BOSC is still a gap that requires further research.

This research investigation has revealed that no evidence exists in the current literature that describes a generic methodology for multi-objective global BOSC optimization. Furthermore, there is no evidence that a general methodology exists that can be applied from the strategic level down to the process level of an entire BOSC. Furthermore, most of the past research on traditional supply chains performance optimization addresses functional products that are optimized using local performance measures. Several researchers highlight the importance of optimization based on global measures (*e.g.*, Schmitz and Platts 2004; Ramdas and Spekman 2000). However, no evidence in the current body of supply chain research exists that considers the optimization of global performance measures for build-to-order supply chains.

CHAPTER 3: RESEARCH METHODOLOGY

3.1. Introduction

This chapter outlines the research methodology. Our research examines the problem of designing the build-to-order supply chain network for any product based on part supplier/manufacturing resource/delivery courier selection. Hence, the ultimate goal in our methodology is to design a build-to-order supply chain for a certain product by selecting one entity from each pool that represents suppliers, resources and couriers. All the selected entities represent the build-to-order supply chain network for a particular product. The selection is based on five measures of performance. The methodology utilizes the SCOR V7.0 as the tool for modeling and measuring the performance of the build-to-order supply chain. However, the methodology is such that any quantitative performance measures can be used.

First, the five supply chain performance measures are formulated from a global perspective. Moreover, a new metric is proposed for assessing and differentiating between the attractiveness of supplier's offer based on savings and net opportunity costs for a build-to-order supply chain. Next, a heuristic is presented to select the best build-to-order supply chain configuration of suppliers, manufacturing resources and delivery couriers.

3.2. The General Build-To-Order Supply Chain Network

Typically, a supply chain is represented as a network of arcs and nodes. This is also the case for the build-to-order supply chain (see Figure 3.1) shows a network representation of the general build-to-order supply chain. The nodes represent activities and the arcs represent dependencies. On the supplier side, there exists a pool of suppliers that extend from the very initial suppliers of raw materials until Tier 1 suppliers who are usually co-located with the focal company. Little to no inventory buffers are kept along the supply chain. For every product's part category, a pool of suppliers is available from which the focal company can select one or more suppliers to supply that part. For example, part category *N* in Figure 3.1 can be supplied by any supplier (1 to *n*) in the pool that extend from N_1 to N_n. Tier 1 suppliers typically feed the focal company in a Just-in-Time basis.

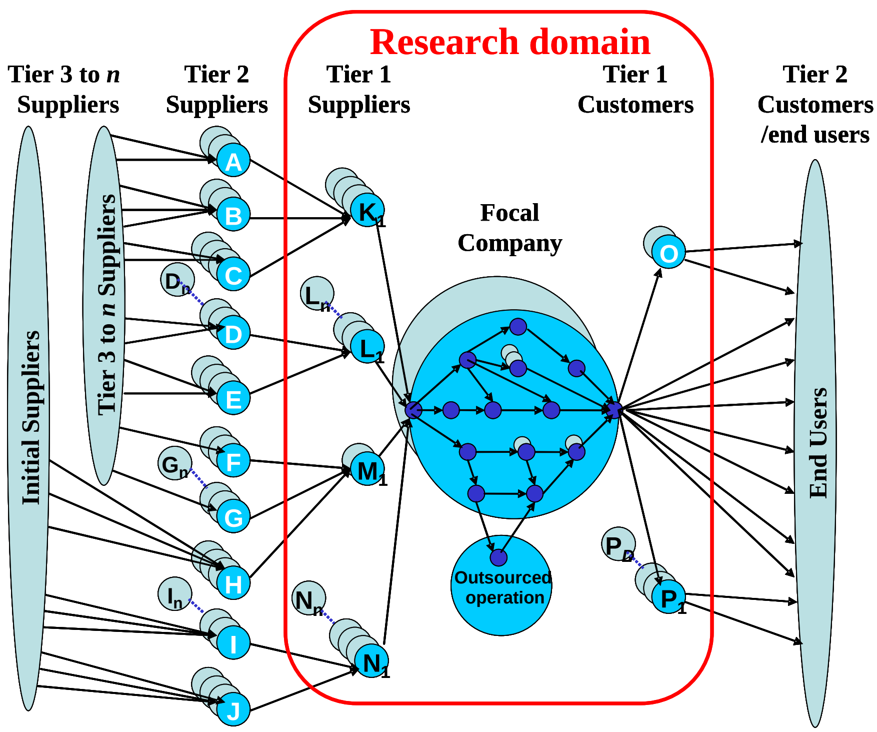


Figure 3.1. A general build-to-order supply chain network.

The focal company could be a manufacturing facility, an assembler, or a virtual enterprise. Each process step is represented by a node. A pool at a certain node represents the number of resources that are available at that node. The arcs represent the sequence of operations a certain product should follow. The focal company could even outsource some or all of its operations to subcontractors.

As soon as the product becomes ready, Tier 1 customers (delivery couriers) retrieve the product from the focal company and ship it directly to the ultimate customers (End Users). A set of couriers are available to serve each customer's region, which are represented by a pool. For example, to ship a product to an end user in the region P, one of the couriers will be selected from the pool of couriers D that extend from P_1 to P_D.

3.3. A Simplified Build-to-Order Supply Chain Network

We limit the scope of the problem and look at the focal company with Tier 1 suppliers and Tier 1 customers. The reason we select this portion of the build-to-order supply chain is that this is the most generic part in all build-to-order supply chains. If we are able to optimize our build-to-order supply chain network for these three stages, we should be able to extend the results to include the whole network.

The problem is simplified as shown in the Figure 3.2, where a set of Tier 1 suppliers are available for each part category p ($p \in \{1, \ldots, P\}$) within the product assembly. In the simplified network, the focal company consists of two serial processes, $b = 1$ and $b = 2$. A set of M_b alternative manufacturing resources are available at each process b. Moreover, a set of delivery couriers D are available for delivering the product to the ultimate customer.

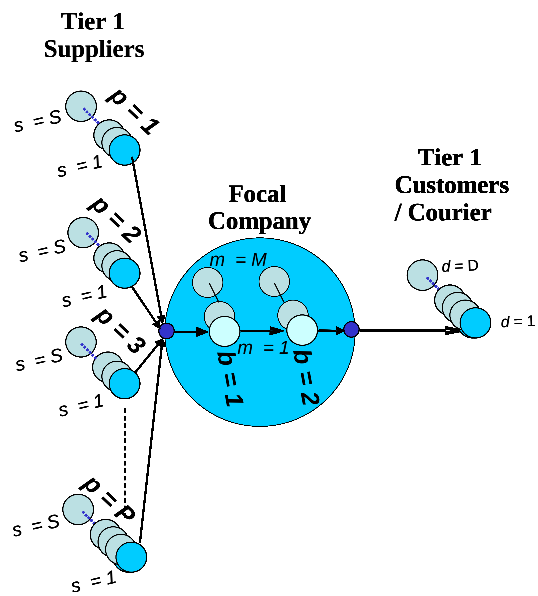


Figure 3.2. Simplified build-to-order supply chain network.

For this analysis, we assume that this simplified supply chain network will only produce one type of product, and that product will require exactly one unit from each part category, each process step, and one delivery courier. Furthermore, only one supplier is selected to supply a part category, only one resource is selected for each process step and only one delivery courier is selected for product delivery to the customer.

The common five SCOR performance measures are used to assess the performance of the build-to-order supply chain entities. However, the SCOR model quantifies supply chain entity's average performance measures and does not consider the stochastic aspect of supply chain entity's performance. Hence, we use the average SCOR model performance measures in this research.

3.4. Modeling the Build-to-Order Supply Chain Global Performance Measures

The majority of past research and current practice in supply chain management have aggregated their supply chains regardless of product types, and assess the performance of their aggregate set of suppliers domain, the performance of their total manufacturing processes domain, as well as the performance of their delivery couriers, regardless of the product types, as shown in Figure 3.3.

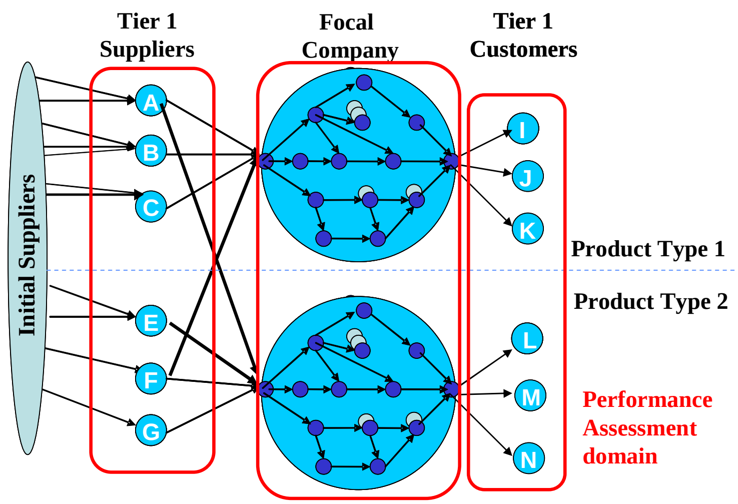


Figure 3.3. Traditional supply chain performance assessment modeling approach.

Our modeling approach is based on subdividing the focal company's supply chain into several supply chains based on product types, *i.e.,* for every different product type, there is a separate supply chain. For example, if Supplier A produces parts to both Product 1 and Product 2, Supplier A's performance will be assessed separately for each product as shown in Figure 3.4.

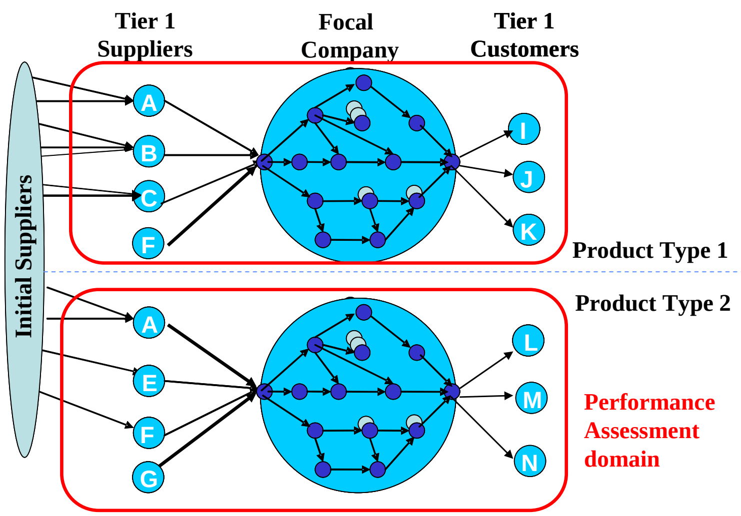


Figure 3.4. Performance assessment by product type.

We now define the build-to-order supply chain performance measures that are used in this research.

Responsiveness: According to SCOR V7.0, the responsiveness of any supply chain entity is measured in terms of average order fulfillment cycle time in units of days (SCC 2005), which is in units of days. The fewer number of days to fill an order, the more responsive the supply chain entity is.

Flexibility: In SCOR V7.0, the flexibility of any supply chain entity is measured in terms of number of days needed required to satisfy a 20% unplanned increase in the number of product orders from customers. The fewer number of days required to fulfill the 20% increase in customer orders means the more flexible that supply chain entity is.

Reliability: The local reliability of any traditional supply chain entity is measured in terms of percentage of perfect orders fulfilled to the direct customer (SCC 2005). The perfect order is defined as the correct order, to the correct customer with the correct documentation and the correct product specifications in the specified correct time (SCC 2005). The larger the percentage of perfect orders fulfilled, the more reliable the supply chain entity is. For a certain order, any delay at any stage, or any non-conformance along the supply process directly impacts the perfect fulfillment of that order.

Cost: In SCOR, the cost to manage the supply chain is defined as the sum of all direct and indirect expenses associated with the production of the product or service (SCC 2005). Therefore, in this research, the total cost represents the summation of all direct and indirect costs, as well as the material costs for each tier.

Asset Management: Asset management is calculated (according to SCOR V7.0) for supply chains through return on supply chain fixed assets and cash-to-cash cycle time, which is the payback period for the return on an investment to flow back into the supply chain organization after it has been spent for raw materials (SCC 2005). However, the current method for quantifying cash-to-cash cycle time is not applicable for the case of BOSCs due to the presence of minimal amounts of inventories. Moreover, the high competition between suppliers and the high responsiveness needed for the case of BOSC results in having the suppliers delivering the required materials quickly, while allowing the focal company some time before the payments for the supplied parts are due to the supplier.

3.4.1. The Importance of the Part Payment Lead Time

Since the build-to-order product lifecycles are relatively short compared to the make-to-stock products of build-to-forecast supply chains, the time before the first payment is made to the parts suppliers can make up a large proportion of the entire product lifecycle and should not be neglected. This time is called the *part payment lead time*, and it is a privilege given by the supplier to the focal company. The lead time starts from the moment the focal company places the part order with the supplier until the payment for that order becomes due to the supplier. It is difficult to decide the best supplier without taking in consideration the part payment lead time to the supplier, especially for the initially-ordered part quantities.

Build-to-forecast supply chains typically ignore the time needed before processing the payments of first-ordered quantities to the suppliers, where they only evaluate their asset management through the steady-state operation after the supply chain network has become stabilized. However, the agile nature of products handled through build-to-order supply chains could result in handling products that have significantly short lifecycles, perhaps of two years, or less in some cases (Terry 2005). This necessitates the importance of evaluating suppliers based on the amount of profit opportunity achieved from delayed payments for ordered materials (parts, components, subassemblies) to suppliers at the initial operation of the build-to-order supply chain. Hence, cash-to-cash cycle time for asset management is replaced by a proposed metric called *Business Sales and Profit Opportunity (BSPO)*.

BSPO is measured from a focal company perspective with respect to Tier 1 suppliers. It is represented as sales and profit opportunity resulting from delayed payments for parts supplied, given the suppliers' cost and responsiveness for supplying each part category. Hence, the amount of profit opportunity achieved from delayed payments to parts suppliers at the initial operation of the build-to-order supply chain are used as a method of assessing the "attractiveness" of selecting a given supplier. This opportunity is considered as one measure for evaluating the performance of parts supplied and selecting the optimal supplier from within a given pool of suppliers at each part category.

Figure 3.5 illustrates the general cash flow when selecting a supplier based on the proposed BSPO metric. As previously mentioned, the supplier's payment lead time can be relatively large compared to the innovative product lifecycle in a build-to-order supply chain.

For every supplier *s* of part category *p* of product type *t*, the manufacturing and delivery costs as well as the sales revenue are represented by a uniform cash flow series that start as soon as the requested parts are received. The part costs to the focal company begin at the end of the part payment lead time of that supplier. The resulting profit is shown in Figure 3.6. Hence, the supplier that allows higher profit at an earlier stage is preferred.

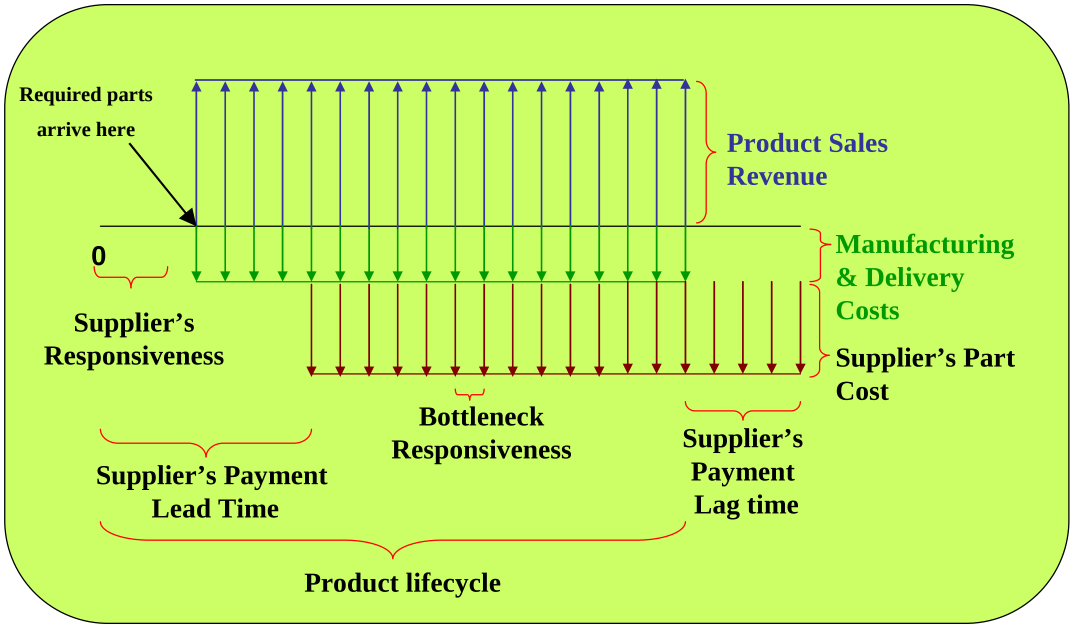


Figure 3.5. General cash flow profile from the focal company perspective when ordering from a part supplier.

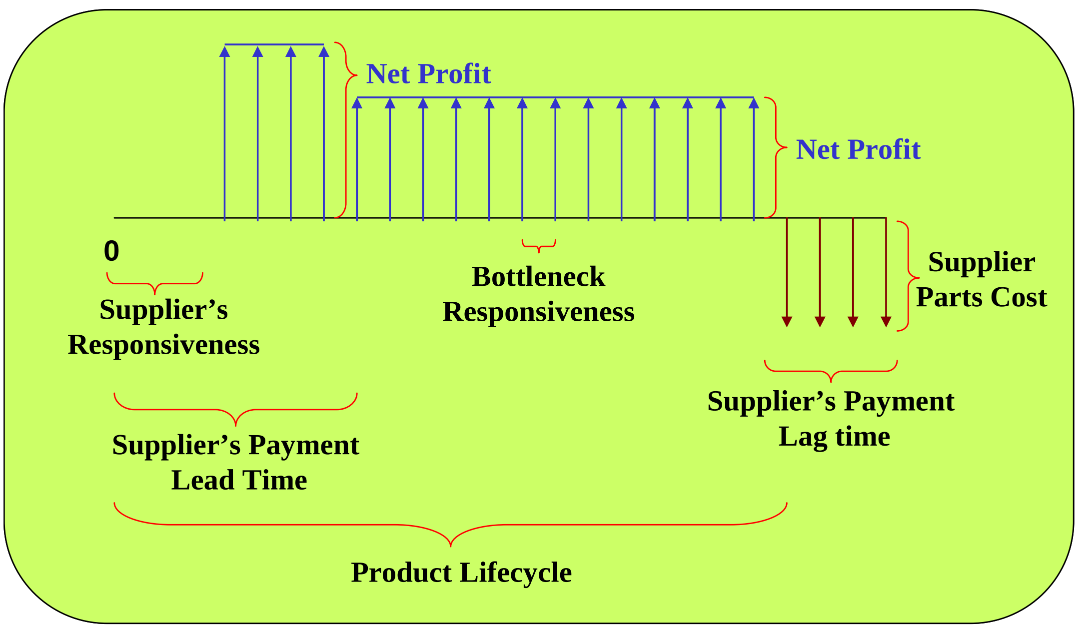


Figure 3.6. Net profit of the focal company perspective when ordering from a part supplier.

3.5. Mathematical Formulation of the Build-to-Order Supply Chain Performance Measures

Before we consider the simultaneous optimization of the five supply chain measures of performance considered in this research, it is necessary to formulate each global performance measure independently from the others. Each formulation will allow the determination of the optimal selection of supply chain entities according to that performance measure alone. Due to the complexity of the performance measures, we must make some simplifying assumptions.

Modeling Assumptions

- Each product consists of only one unit from each part category ($p = 1, \ldots, P$), and the unit from a given part category is sent directly to the focal company and available for use in the manufacturing processes.
- The part quantity per order placed by the focal company with any part supplier is one unit.
- Each of the pool of suppliers for each part category p (S_p) is capable of covering all possible order variations within the same part as per customer requirements.
- The focal company includes only two major manufacturing process steps $B = 2$, and these two process steps are in series.
- The focal company does not outsource any of its operations and processes.
- All delivery couriers D can ship to all customer locations.

The above assumptions are made for the purpose of simplification and abstraction in order to model the general case. However, the mathematical models can be customized for any number of parts or operations for a specific product. Here, we assume that a single customer order for a product is to be fulfilled within the simplified build-to-order supply chain.

Responsiveness (order fulfillment cycle time (days))

<u>Notation and Inputs:</u>

P: total number of part categories

T: total number of product types

Φ_{tp}: number of parts of category p that comprise one unit of product t, where $t = 1, \ldots, T$

U_t: total number of demand of product type t

S_p: total number of suppliers in supplier pool for part category p, where $p = 1, \ldots, P$

B: total number of manufacturing process steps

M_b: total number of manufacturing resources for manufacturing process step b, where $b = 1, \ldots, B$

D: total number of delivery couriers

Responsiveness:

α_{tps}: responsiveness of supplying one unit from part category p by supplier s

β_{tbm}: responsiveness of processing one unit of product t by resource m

χ_{td}: responsiveness of delivering one unit of product t by courier d

C_s: capacity of supplier s

C_m: capacity of manufacturing resource m

C_d: capacity of delivery courier d

Decision Variables:

$$x_{tps} = \begin{cases} 1, & \text{if part category } p \text{ of product } t \text{ is supplied by supplier } s \\ 0, & \text{otherwise} \end{cases}$$

y_{tps}: number of units of parts in category p of product t supplied by supplier s

$$w_{tbm} = \begin{cases} 1, & \text{if product } t \text{ is processed by manufacturing resource } m \text{ at process step } b \\ 0, & \text{otherwise} \end{cases}$$

q_{tbm}: number of units of product type t processed by manufacturing resource m at process step b.

Using the notation and input parameters above, the model formulation to select the optimal set of build-to-order supply chain entities (suppliers, manufacturing processes, and delivery couriers) using responsiveness as the only measure of performance is as follows:

$$\text{Max} \quad \sum_{t=1}^{T}\left(\max_{p=1}^{P}\left\{ \min_{s=1}^{S_p}\left\{ \alpha_{tps} x_{tps} y_{tps} \right\} \right\} \right) + \sum_{t=1}^{T}\sum_{b=1}^{B}\left(\min_{m=1}^{M_b}\left\{ \beta_{tbm} q_{tbm} w_{tbm} \right\} \right) + \min_{d=1}^{D}\left\{ \sum_{t=1}^{T} \chi_{dt} U_t \right\} \tag{3.1}$$

$$\text{s.t.} \quad \sum_{s=1}^{S_p} y_{tps} = \Phi_{tp} q_t \qquad \forall t = 1, \ldots, T; \forall p = 1, \ldots, P \tag{3.2}$$

$$y_{tps} \le C_s \qquad \forall t = 1, \ldots, T; \forall p = 1, \ldots, P; \forall s = 1, \ldots, S_p \tag{3.3}$$

$$\sum_{s=1}^{S_p} x_{tps} = 1 \qquad \forall t = 1, \ldots, T; \forall p = 1, \ldots, P \tag{3.4}$$

$$\sum_{m=1}^{M_b} q_{tbm} = U_t \qquad \forall t = 1, \ldots, T; \forall b = 1, \ldots, B \tag{3.5}$$

$$\sum_{b=1}^{B} q_{bm} w_{tbm} \le C_m \qquad \forall t = 1, \ldots, T; \forall m = 1, \ldots, M_b \tag{3.6}$$

$$\sum_{m=1}^{M_b} w_{tbm} = 1 \qquad \forall t = 1, \ldots, T; \forall b = 1, \ldots, B \tag{3.7}$$

$$\sum_{t=1}^{T} U_t \le C_d \qquad \forall d = 1, \ldots, D \tag{3.8}$$

$$y_{tps} \ge 0, \text{ integer} \qquad \forall t = 1, \ldots, T; \forall p = 1, \ldots, P; \forall s = 1, \ldots, S_p \tag{3.9}$$

$$x_{tps} \in \{0,1\} \qquad \forall t = 1, \ldots, T; \forall p = 1, \ldots, P; \forall s = 1, \ldots, S_p \tag{3.10}$$

$$q_{tbm} \ge 0, \text{ integer} \qquad \forall t = 1, \ldots, T; \forall b = 1, \ldots, B; \forall m = 1, \ldots, M_b \tag{3.11}$$

$$w_{tbm} \in \{0,1\} \qquad \forall t = 1, \ldots, T; \forall b = 1, \ldots, B; \forall m = 1, \ldots, M_b \tag{3.12}$$

Eq. (3.1) is the responsiveness objective function. The maximum responsiveness is achieved by minimizing the order fulfillment cycle time at all three stages (Tier 1 suppliers, manufacturing at the focal company, and Tier 1 customers). The first term represents the responsiveness objective associated with the inbound logistics of obtaining the low-level product parts, components and subassemblies prior to processing. The objective is to select a supplier for each part category who will contribute to the minimum order fulfillment cycle time. The maximum order fulfillment cycle time across all the parts will determine the global supplier order fulfillment cycle time. The second term represents the responsiveness to manufacture a number of units of product t. The "min" relationship represents the selection of the manufacturing resource m at process step b for product t that has the minimum order fulfillment cycle time. The last term represents the responsiveness objective of the outbound logistics associated with the product direct delivery to customer through a third-party delivery courier service. Here, we assume that the focal company always selects the delivery courier with the maximum responsiveness (*i.e.*, the minimum delivery time) to deliver all quantities of product types to all customers. Therefore, this third term will be the same regardless of the parts suppliers and manufacturing resources selected.

Constraint (3.2) ensures that the total number of parts supplied across all suppliers S_p for part category *p* will be equal to the number of parts required to manufacture the total number of whole units for each product type *t*. Constraint (3.3) ensures that the number of parts of category *p* supplied by supplier *s* for each product *t* will not exceed the capacity of supplier *s*. Constraint (3.4) is a constraint to ensure that only one supplier *s* will be selected for each part category *p* for product type *t*. Constraint (3.5) ensures that the number of whole units of product type *t* processed by resource *m* will be equal to the demand for product type *t*. Constraint (3.6) ensures that the number of whole units of product type *t* processed by resource *m* will not exceed the capacity of resource *m*. Eq. (3.7) is a constraint to ensure that only one manufacturing resource *m* will be selected for each process step *b* for product type *t*. Constraint (3.8) ensures that the number of whole units of product type *t* required for delivery by courier *d* will not exceed the capacity of courier *d.* Constraints (3.9) are the non-negativity and integrality constraints for number of parts of category *p* of product *t* supplied by supplier *s*. Constraint (3.10) is a binary constraint for part category *p* for product type *t* is supplied by supplier *s*; 1, if part category *p* for product type *t* is supplied by supplier *s*; 0, otherwise. Constraint (3.11) are the non-negativity and integrality constraints for number of units of product type *t* processed by resource *m* for each process step *b*. Eq. (3.12) is a binary constraint for product type *t* is processed by resource *m* for process step *b*; 1, product type *t* is processed by resource *m* for process step *b*; 0, otherwise.

Numerical Example for Computing the Build-to-Order Supply Chain Global Responsiveness Performance

Figure 3.7 shows a manufacturing supply chain that consists of nine suppliers for three different part categories. Each part category can be produced by any of its three alternative suppliers. There are two manufacturing processes that have three available alternative resources each. Finally, there are three alternative delivery couriers that are available to ship the final product.

In other words,

- Suppliers s_1, s_2, and s_3 are capable of supplying Part p_1,
- Suppliers s_4, s_5, and s_6 are capable of supplying Part p_2,
- Suppliers s_7, s_8, and s_9 are capable of supplying Part p_3,
- Manufacturing Resources m_1, m_2, and m_3 are available at Process b_1,
- Manufacturing Resources m_4, m_5, and m_6 are available at Process b_2, and
- Delivery Couriers d_1, d_2, and d_3 can deliver the final product.

The responsiveness values are given in Figure 3.7 for each entity at the three stages of the supply chain and the entities with the best responsiveness at each stage of the supply chain are shown in red. By assessing the performance of supply chain entities based on their responsiveness values only, the best responsiveness (*i.e.*, smallest number of days) for:

- Part p_1 = 8 days using Supplier s_2,
- Part p_2 = 5 days using Supplier s_6,
- Part p_3 = 7 days using Supplier s_7,

- Process Step b_1 = 3 days using Resource m_3,
- Process Step b_2 = 4 days using Resource m_5, and
- Delivery = 2 days using Courier d_3.

Therefore, the supply chain configuration to realize the best overall supply chain responsiveness is the above entities. As a result, the best independent global supply chain responsiveness is max{8, 5, 7} + 3 + 4 + 2 = 17 days. The supplier of Part p_1 can be viewed as the constraining entity (or bottleneck) within the supply chain since it has the worst individual responsiveness (*i.e.*, the maximum number of days) of eight days.

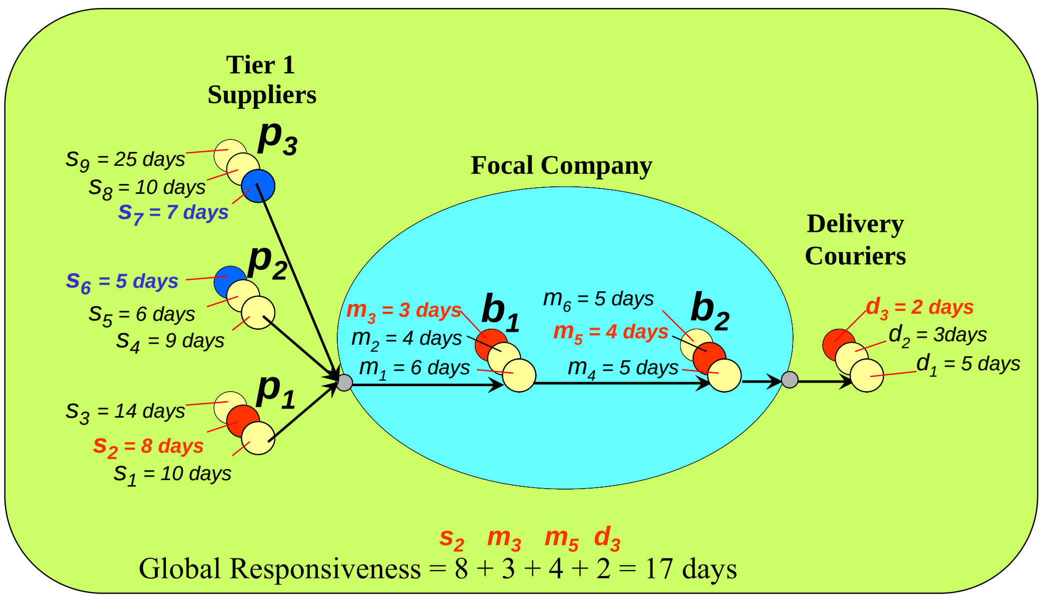


Figure 3.7. Numerical example for BOSC global responsiveness.

Flexibility (number of days needed for (ρ×100%) unplanned increase in order quantities)

<u>Additional Notation and Inputs:</u>

f_{tps}: flexibility of supplying one unit from part category p by supplier s

o_{tbm}: flexibility of processing one unit of product t by manufacturing resource m

v_{dt}: flexibility of delivering one unit of product t by courier d

Decision Variables:

$$x_{tps} = \begin{cases} 1, & \text{if part category } p \text{ of product } t \text{ is supplied by supplier } s \\ 0, & \text{otherwise} \end{cases}$$

y_{tps}: number of units of parts in category p of product t supplied by supplier s

$$w_{tbm} = \begin{cases} 1, & \text{if product } t \text{ is processed by manufacturing resource } m \text{ at process step } b \\ 0, & \text{otherwise} \end{cases}$$

q_{tbm}: number of units of product type t processed by manufacturing resource m at process step b.

$$\text{Max} \quad \sum_{t=1}^{T}\left(\max_{p=1}^{P}\left\{\min_{s=1}^{S_p}\left\{f_{tps}x_{tps}\rho y_{tps}\right\}\right\}\right)+\sum_{t=1}^{T}\sum_{b=1}^{B}\left(\min_{m=1}^{M_b}\left\{o_{tbm}w_{tbm}\rho q_{tbm}\right\}\right) + \min_{d=1}^{D}\left\{\sum_{t=1}^{T}v_{dt}\rho U_t\right\} \tag{3.13}$$

$$\text{s.t.} \quad \sum_{s=1}^{S_p} y_{tps} = \Phi_{pt} q_t \qquad \forall t = 1, \ldots, T; \forall p = 1, \ldots, P \tag{3.14}$$

$$y_{tps} \le C_s \qquad \forall t = 1, \ldots, T; \forall p = 1, \ldots, P; \forall s = 1, \ldots, S_p \tag{3.15}$$

$$\sum_{s=1}^{S_p} x_{tps} = 1 \qquad \forall t = 1, \ldots, T; \forall p = 1, \ldots, P \tag{3.16}$$

$$\sum_{m=1}^{M_b} q_{tbm} = U_t \qquad \forall t = 1, \ldots, T; \forall b = 1, \ldots, B \tag{3.17}$$

$$\sum_{b=1}^{B} q_{bm} w_{tbm} \le C_m \qquad \forall t = 1, \ldots, T; \forall m = 1, \ldots, M_b \tag{3.18}$$

$$\sum_{m=1}^{M_b} w_{tbm} = 1 \qquad \forall t = 1, \ldots, T; \forall b = 1, \ldots, B \tag{3.19}$$

$$\sum_{t=1}^{T} U_t \le C_d \qquad \forall d = 1, \ldots, D \tag{3.20}$$

$$q_{tbm} \ge 0, \text{ integer} \qquad \forall t = 1, \ldots, T; \forall b = 1, \ldots, B; \forall m = 1, \ldots, M_b \tag{3.21}$$

$$w_{tbm} \in \{0,1\} \qquad \forall t = 1, \ldots, T; \forall b = 1, \ldots, B; \forall m = 1, \ldots, M_b \tag{3.22}$$

$$y_{tps} \ge 0, \text{ integer} \qquad \forall t = 1, \ldots, T; \forall p = 1, \ldots, P; \forall s = 1, \ldots, S_p \tag{3.23}$$

$$x_{tps} \in \{0,1\} \qquad \forall t = 1, \ldots, T; \forall p = 1, \ldots, P; \forall s = 1, \ldots, S_p \tag{3.24}$$

Eq. (3.13) is the flexibility objective function. The maximum flexibility is achieved by minimizing the number of days needed for (ρ×100%) unplanned increase in order quantities. The first term represents the supplier for each part who will contribute to the minimum number of days needed for (ρ×100%) unplanned increase in order quantities, while the "max" relationship represents the critical part whose optimum supplier has the maximum number of days needed for (ρ×100%) unplanned increase in order quantities among all the parts. The part with maximum number of days needed, will represent the number of days needed for parts supply in the global flexibility equation. The second term represents the flexibility of manufacturing a number of units of product *t*. The "min" relationship represents the minimum number of days needed for (ρ×100%) unplanned increase in order quantities required for manufacturing product *t* by resource *m* at process *b*. The last term, similar to responsiveness, we assume that the focal company always selects the delivery courier with the maximum flexibility, which is the minimum number of days needed for unplanned increase in delivery quantities, to deliver all quantities of product types all customers.

Constraint (3.14) ensures that the total number of parts supplied across all suppliers S_p for part category *p* will be equal to the number of parts required to manufacture the total number of whole units for each product type *t*. Constraint (3.15) ensures that the number of parts of category *p* supplied by supplier *s* for each product *t* will not exceed the capacity of supplier *s*. Constraint (3.16) is a constraint to ensure that only one supplier *s* will be selected for each part category *p* for product type *t*. Constraint (3.17) ensures that the number of whole units of product type *t* processed by resource *m* will be equal to the demand for product type *t*. Constraint (3.18) ensures that the number of whole units of product type *t* processed by resource *m* will not exceed the capacity of resource *m.* Eq. (3.19) is a constraint to ensure that only one resource *m* will be selected for each process step *b* for product type *t*. Constraint (3.20) ensures that the number of whole units of product type *t* required for delivery by delivery courier *d* will not exceed the capacity of delivery courier *d.* Constraint (3.21) are the non-negativity and integrality constraints for number of units of product type *t* processed by resource *m* for every process step *b*. Eq. (3.22) is a binary constraint for product type *t* is processed by manufacturing resource *m* for process step *b*; 1, product type *t* is processed by manufacturing resource *m* for process step *b*; 0, otherwise. Constraint (3.23) are the non-negativity and integrality constraints for number of parts of category *p* supplied by supplier *s*. Eq. (3.24) is a binary constraint for part category *p* for product type *t* is supplied by supplier *s*; 1, if part category *p* for product type *t* is supplied by supplier *s*; 0, otherwise.

Numerical Example for Computing the Build-to-Order Supply Chain Global Flexibility Performance

We refer to the build-to-order supply chain shown in Figure 3.7. However, suppose we consider only the flexibility of each supplier, manufacturing resource and courier in determining the best supply chain configuration. The flexibility performance values are given in Figure 3.8 in terms of the number of days – the smaller the value, the better. Therefore, the best flexibility values at each stage of the supply chain are:

- Part p_1 = 0.5 days using Supplier s_3,
- Part p_2 = 1 day using Supplier s_5,

- Part p_3 = 0.7 days using Supplier s_7,
- Process b_1 = 1 day using Resource m_3,
- Process b_2 = 0.4 days using Resource m_5, and
- Delivery = 0.2 days using Courier d_1.

These values are shown in red in Figure 3.8. Thus, the maximum independent global flexibility for the supply chain configuration in the figure is max{0.5, 1, 0.7} + 1 + 0.4 + 0.2 = 2.6 days. According to the local flexibility performance values, both Supplier s_5 and the Manufacturing Resource m_3 are the bottleneck entities in this supply chain configuration. However, as shown in the build-to-order supply chain responsiveness example, Supplier s_2 is the sole bottleneck entity.

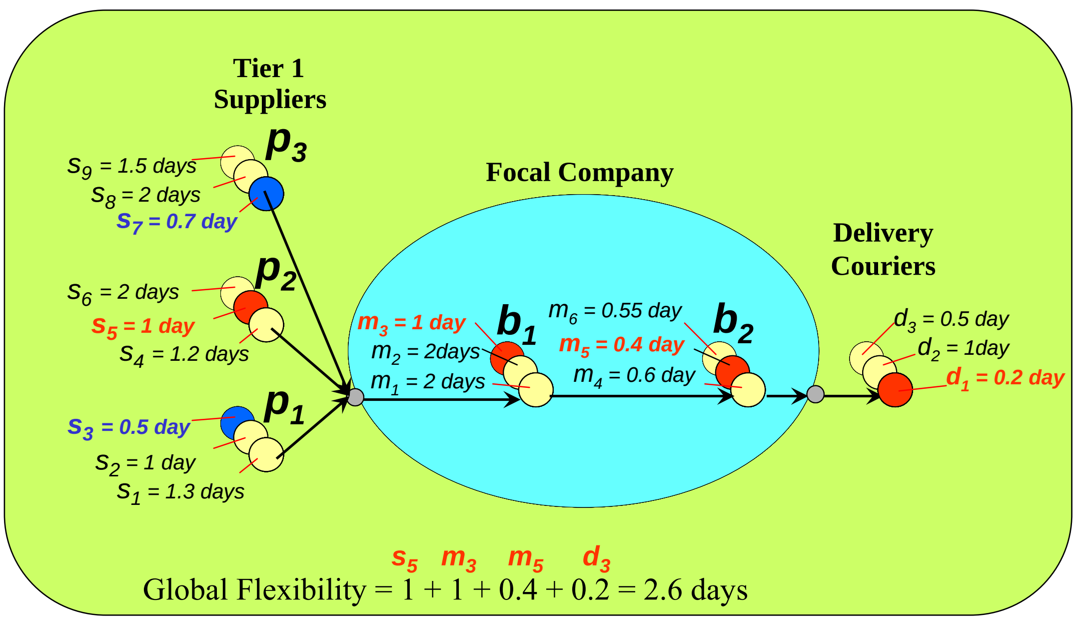


Figure 3.8. Numerical example for build-to-order supply chain global flexibility.

Reliability (Perfect Order Fulfillment (%))

Additional Notation and Inputs:

r_{tps}: reliability of supplying one unit from part category p by supplier s

g_{tbm}: reliability of processing one unit of product t by resource m

l_{dt}: reliability of delivering one unit of product t by courier d

Decision Variables:

$$x_{tps} = \begin{cases} 1, & \text{if part category } p \text{ of product } t \text{ is supplied by supplier } s \\ 0, & \text{otherwise} \end{cases}$$

y_{tps}: number of units of parts in category p of product t supplied by supplier s

$$w_{tbm} = \begin{cases} 1, & \text{if product } t \text{ is processed by manufacturing resource } m \text{ at process step } b \\ 0, & \text{otherwise} \end{cases}$$

q_{tbm}: number of units of product type t processed by manufacturing resource m at process step b.

$$\text{Max} \quad \left(\prod_{t=1}^{T} \prod_{p=1}^{P} \prod_{\substack{s=1 \\ x_{tps} \neq 0}}^{S_p} x_{tps} y_{tps} r_{tps} \right) \left(\prod_{t=1}^{T} \prod_{b=1}^{B} \prod_{\substack{m=1 \\ w_{tbm} \neq 0}}^{M_b} w_{tbm} q_{tbm} g_{tbm} \right) \left(\max_{d=1}^{D} \left\{ \sum_{t=1}^{T} l_{dt} \right\} \right) \tag{3.25}$$

$$\text{s.t.} \quad \sum_{s=1}^{S_p} y_{tps} = \Phi_{pt} q_t \qquad \forall t = 1, \ldots, T; \forall p = 1, \ldots, P \tag{3.26}$$

$$y_{tps} \leq C_s \qquad \forall t = 1, \ldots, T; \forall p = 1, \ldots, P; \forall s = 1, \ldots, S_p \tag{3.27}$$

$$\sum_{s=1}^{S_p} x_{tps} = 1 \qquad \forall t = 1, \ldots, T; \forall p = 1, \ldots, P \tag{3.28}$$

$$\sum_{m=1}^{M_b} q_{tbm} = U_t \qquad \forall t = 1, \ldots, T; \forall b = 1, \ldots, B \tag{3.29}$$

$$\sum_{b=1}^{B} q_{bm} w_{tbm} \leq C_m \qquad \forall t = 1, \ldots, T; \forall m = 1, \ldots, M_b \tag{3.30}$$

$$\sum_{m=1}^{M_b} w_{tbm} = 1 \qquad \forall t = 1, \ldots, T; \forall b = 1, \ldots, B \tag{3.31}$$

$$\sum_{t=1}^{T} U_t \leq C_d \qquad \forall d = 1, \ldots, D \qquad (3.32)$$

$$y_{tps} \geq 0, \text{ integer} \qquad \forall t = 1, \ldots, T; \forall p = 1, \ldots, P; \forall s = 1, \ldots, S_p \qquad (3.33)$$

$$x_{tps} \in \{0,1\} \qquad \forall t = 1, \ldots, T; \forall p = 1, \ldots, P; \forall s = 1, \ldots, S_p \qquad (3.34)$$

$$q_{tbm} \geq 0, \text{ integer} \qquad \forall t = 1, \ldots, T; \forall b = 1, \ldots, B; \forall m = 1, \ldots, M_b \qquad (3.35)$$

$$w_{tbm} \in \{0,1\} \qquad \forall t = 1, \ldots, T; \forall b = 1, \ldots, B; \forall m = 1, \ldots, M_b \qquad (3.36)$$

Eq. (3.25) is the reliability objective function, which is a multiplicative relationship of three terms. The maximum reliability is achieved by maximizing the percent of perfect order fulfillment at each of the three terms. The objective is to select a supplier for each part who will contribute the maximum percentage of perfect order fulfillment, while the "min" relationship represents the critical part, whose optimum supplier has the minimum percentage of perfect order fulfillment among all the parts. The part with minimum percent of perfect order fulfillment will contribute to the calculation of the global percentage of perfect order fulfillment. The second term represents the reliability of manufacturing a number of units of product *t*. The "max" relationship represents the maximum percentage of perfect order fulfillment. Again, we assume that the focal company always selects the delivery courier with the maximum reliability to deliver all quantities of product types all customers.

Constraint (3.26) ensures that the total number of parts supplied across all suppliers S_p for part category *p* will be equal to the number of parts required to manufacture the total number of whole units for each product type *t*. Constraint (3.27) ensures that the number of parts of category *p* supplied by supplier *s* for each product *t* will not exceed the capacity of supplier *s*. Constraint (3.28) is a constraint to ensure that only one supplier *s* will be selected for each part category *p* for product type *t*. Constraint (3.29) ensures that the number of whole units of product type *t* processed by resource *m* will be equal to the demand for product type *t*. Constraint (3.30) ensures that the number of whole units of product type *t* processed by resource *m* will not exceed the capacity of resource *m.* Constraint (3.31) is a constraint to ensure that only one resource *m* will be selected for each process step *b* for product type *t*. Constraint (3.32) ensures that the number of whole units of product type *t* required for delivery by delivery courier *d* will not exceed the capacity of delivery courier *d.* Constraint (3.33) are the non-negativity and integrality constraints for number of parts of category *p* supplied by supplier *s*. Constraint (3.34) is a binary constraint for part category *p* for product type *t* is supplied by supplier *s*; 1, if part category *p* for product type *t* is supplied by supplier *s*; 0, otherwise. Constraint (3.35) are the non-negativity and integrality constraints for number of units of product type *t* processed by manufacturing resource *m* for every process step *b*. Constraint (3.36) is a binary constraint for product type *t* is processed by manufacturing resource *m* for process step *b*; 1, product type *t* is processed by manufacturing resource *m* for process step *b*; 0, otherwise.

Numerical Example for Computing Build-to-Order Supply Chain Global Reliability Performance

Again, using the same supply chain configuration as in the previous two examples, suppose that each supplier, manufacturing resource and courier has individual reliability measure as shown in Figure 3.9. Then, the best individual reliability performance for each supply chain entity is:

- Part p_1 = 0.93 using Supplier s_2,
- Part p_2 = 0.97 using Supplier s_5,

- Part $p_3 = 0.98$ using Supplier s_7,
- Process $b_1 = 0.99$ using Resource m_2,
- Process $b_2 = 0.98$ using Resource m_4, and
- Delivery = 0.99 using Courier d_2.

Then, Supplier s_2 for Part p_1 is the worst performer among suppliers as it has the lowest reliability performance. The best reliability for the build-to-order supply chain configuration using the above entities is $0.93 \times 0.97 \times 0.98 \times 0.99 \times 0.98 \times 0.99 = 0.85$.

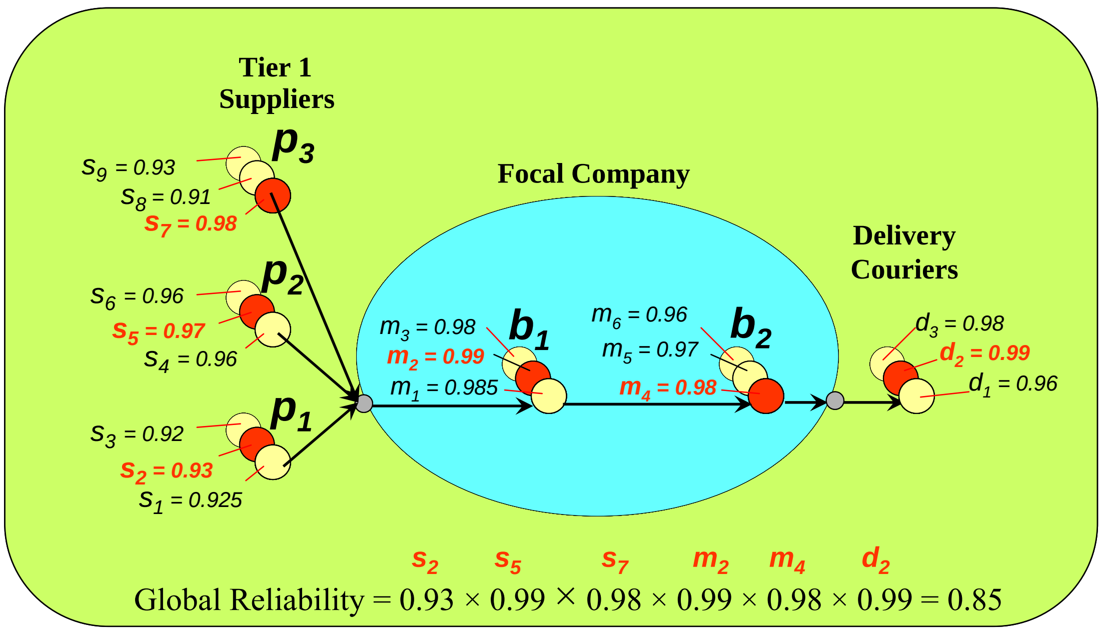


Figure 3.9. Numerical example for build-to-order supply chain global reliability.

Cost

<u>Additional Notation and Inputs:</u>

c_{tps}: cost of producing one unit from part category p by supplier s

a_{tbm}: cost of processing one unit of product t by manufacturing resource m

e_{dt}: cost of delivering one unit of product t by courier d

Decision Variables:

$$x_{tps} = \begin{cases} 1, & \text{if part category } p \text{ of product } t \text{ is supplied by supplier } s \\ 0, & \text{otherwise} \end{cases}$$

y_{tps}: number of units of parts in category p of product t supplied by supplier s

$$w_{tbm} = \begin{cases} 1, & \text{if product } t \text{ is processed by manufacturing resource } m \text{ at process step } b \\ 0, & \text{otherwise} \end{cases}$$

q_{tbm}: number of units of product type t processed by manufacturing resource m at process step b.

$$\text{Min} \quad \sum_{t=1}^{T}\sum_{p=1}^{P_t}\sum_{s=1}^{S_p} c_{tps}x_{tps}y_{tps} + \sum_{t=1}^{T}\sum_{b=1}^{B}\sum_{m=1}^{M_b} a_{tbm}w_{tbm}q_{tbm} + \min_{d=1}^{D}\left\{\sum_{t=1}^{T} e_{dt}U_t\right\} \tag{3.37}$$

$$\text{s.t.} \quad \sum_{s=1}^{S_p} y_{tps} = \Phi_{pt}q_t \qquad \forall t = 1, \ldots, T;\ \forall p = 1, \ldots, P \tag{3.38}$$

$$y_{tps} \le C_s \qquad \forall t = 1, \ldots, T;\ \forall p = 1, \ldots, P;\ \forall s = 1, \ldots, S_p \tag{3.39}$$

$$\sum_{m=1}^{M_b} w_{tbm} = 1 \qquad \forall t = 1, \ldots, T;\ \forall p = 1, \ldots, P \tag{3.40}$$

$$\sum_{t=1}^{T} U_t \le C_d \qquad \forall t = 1, \ldots, T;\ \forall b = 1, \ldots, B \tag{3.41}$$

$$\sum_{s=1}^{S_p} x_{tps} = 1 \qquad \forall t = 1, \ldots, T;\ \forall m = 1, \ldots, M_b \tag{3.42}$$

$$\sum_{m=1}^{M_b} q_{tbm} = U_t \qquad \forall t = 1, \ldots, T;\ \forall b = 1, \ldots, B \tag{3.43}$$

$$\sum_{b=1}^{B} q_{bm}w_{tbm} \le C_m \qquad \forall d = 1, \ldots, D \tag{3.44}$$

$$y_{tps} \ge 0, \text{ integer} \qquad \forall t = 1, \ldots, T;\ \forall p = 1, \ldots, P;\ \forall s = 1, \ldots, S_p \tag{3.45}$$

$$x_{tps} \in \{0,1\} \qquad \forall t = 1, \ldots, T;\ \forall p = 1, \ldots, P;\ \forall s = 1, \ldots, S_p \tag{3.46}$$

$$q_{tbm} \ge 0, \text{ integer} \qquad \forall t = 1, \ldots, T;\ \forall b = 1, \ldots, B;\ \forall m = 1, \ldots, M_b \tag{3.47}$$

$$w_{tbm} \in \{0,1\} \qquad \forall t = 1, \ldots, T;\ \forall b = 1, \ldots, B;\ \forall m = 1, \ldots, M_b \tag{3.48}$$

Eq. (3.37) is the cost objective function. The minimum cost is achieved by minimizing the costs associated with all supply chain entities. The first term represents the cost objective associated with the in-bound logistics of obtaining the low-level product parts, components and sub-assemblies from suppliers prior to manufacturing. The second term represents the cost of manufacturing a number of units of product *t*. The last term represents the cost objective of the outbound logistics associated with the product direct delivery to customer through a third-party delivery courier service. As before, we assume that the focal company always selects the delivery courier with the minimum cost to deliver all quantities of product types all customers.

Constraint (3.38) ensures that the total number of parts supplied across all suppliers S_p for part category *p* will be equal to the number of parts required to manufacture the total number of whole units for each product type *t*. Constraint (3.39) ensures that the number of parts of category *p* supplied by supplier *s* for each product *t* will not exceed the capacity of supplier *s*. Constraint (3.40) is a constraint to ensure that only one supplier *s* will be selected for each part category *p* for product type *t*. Constraint (3.41) ensures that the number of whole units of product type *t* processed by manufacturing resource *m* will be equal to the demand for product type *t*. Constraint (3.42) ensures that the number of whole units of product type *t* processed by resource *m* will not exceed the capacity of resource *m.* Constraint (3.43) is a constraint to ensure that only one resource *m* will be selected for each manufacturing process step *b* for product type *t*. Constraint (3.44) ensures that the number of whole units of product type *t* required for delivery by delivery courier *d* will not exceed the capacity of courier *d.* Constraint (3.45) are the non-negativity and integrality constraints for number of parts of category *p* supplied by supplier s. Constraint (3.46) is a binary constraint for part category p for product type t is supplied by supplier s; 1, if part category p for product type t is supplied by supplier s; 0, otherwise. Constraint (3.47) are the non-negativity and integrality constraints for number of units of product type t processed by resource m for every process step b. Eq. (3.48) is a binary constraint for product type t is processed by resource m for process step b; 1, product type t is processed by resource m for process step b; 0, otherwise.

Numerical Example for Computing Build-to-Order Supply Chain Global Cost Performance

Using the previous supply chain configuration, Figure 3.10 shows the same example supply chain with individual unit costs for the suppliers, manufacturing resources and couriers. The minimum cost for:

- Part p_1 = \$45 using Supplier s_3,
- Part p_2 = \$95 using Supplier s_4,
- Part p_3 = \$50 using Supplier s_9,
- Process b_1 = \$50 using Resource m_1,
- Process b_2 = \$40 using Resource m_6, and
- Delivery = \$30 using Courier d_3.

Hence, the minimum global cost = \$45 + \$95 + \$50 + \$50 + \$40 + \$30 = \$310.

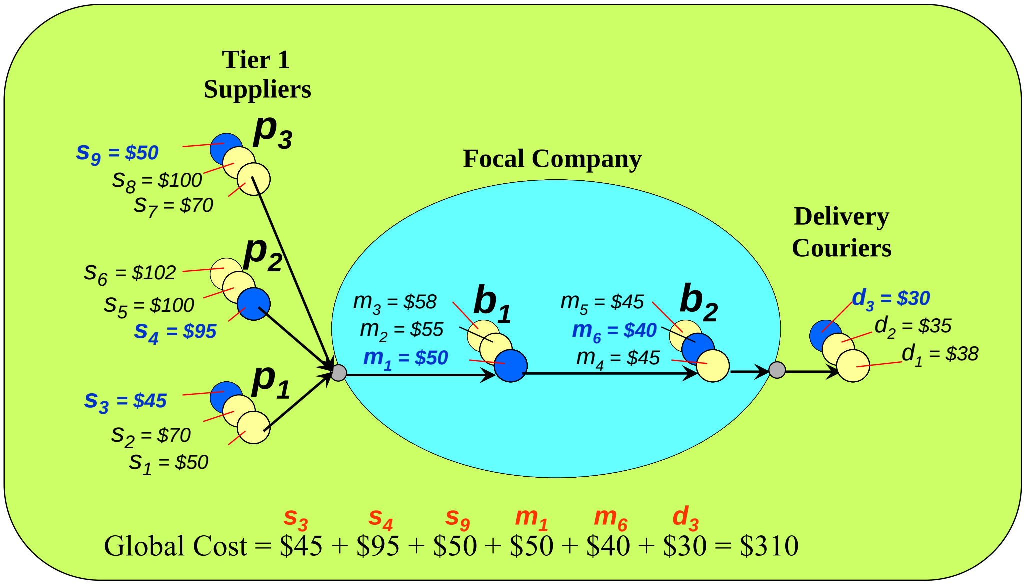


Figure 3.10. Numerical example for build-to-order supply chain global cost.

Asset Management (Business Sales and Profit Opportunity ($))

<u>Additional Notation and Inputs:</u>

ϖ: the bottleneck process step for the supply chain

U_{tps}: number of product units of type t manufactured during the product lifetime ς_t

c_{tps}: cost of producing one unit from part category p by supplier s

a_{tbm}: cost of processing one unit of product t by manufacturing resource m

e_{dt}: cost of delivering one unit of product t by courier d

β_{tps}: responsiveness of processing one unit of product t by manufacturing resource m

χ_{tps}: responsiveness of delivering one unit of product t by courier d

$C_{\varpi m}$: capacity of manufacturing resource m at the bottleneck process ϖ

ς_{tps}: lifetime of product type t when using supplier s for part category p

θ_t: unit sales price of product t

τ: discrete compound interest rate for unit time equivalent to bottleneck responsiveness

Decision Variables:

$$x_{tps} = \begin{cases} 1, & \text{if part category } p \text{ of product } t \text{ is supplied by supplier } s \\ 0, & \text{otherwise} \end{cases}$$

y_{tps}: number of units of parts in category p of product t supplied by supplier s

$$w_{tbm} = \begin{cases} 1, & \text{if product } t \text{ is processed by manufacturing resource } m \text{ at process step } b \\ 0, & \text{otherwise} \end{cases}$$

q_{tbm}: number of units of product type t processed by manufacturing resource m at process step b.

$$\text{Max} \quad \sum_{t=1}^{T}\sum_{p=1}^{P_t}\sum_{s=1}^{S_p}\left(\eta_{tps} - \xi_t\right) \tag{3.49}$$

$$\text{s.t.} \quad \sum_{s=1}^{S_p} y_{tps} = \Phi_{pt} q_t \qquad \forall t = 1, \ldots, T; \forall p = 1, \ldots, P \tag{3.50}$$

$$y_{tps} \le C_{ps} \qquad \forall t = 1, \ldots, T; \forall p = 1, \ldots, P; \forall s = 1, \ldots, S_p \tag{3.51}$$

$$\sum_{s=1}^{S_p} x_{tps} = 1 \qquad \forall t = 1, \ldots, T; \forall p = 1, \ldots, P \tag{3.52}$$

$$\sum_{m=1}^{M_b} q_{tbm} = U_t \qquad \forall t = 1, \ldots, T; \forall b = 1, \ldots, B \tag{3.53}$$

$$\sum_{b=1}^{B} q_{bm} w_{tbm} \le C_m \qquad \forall t = 1, \ldots, T; \forall m = 1, \ldots, M_b \tag{3.54}$$

$$\sum_{m=1}^{M_b} w_{tbm} = 1 \qquad \forall t = 1, \ldots, T; \forall b = 1, \ldots, B \tag{3.55}$$

$$\sum_{t=1}^{T} U_t \le C_d \qquad \forall d = 1, \ldots, D \tag{3.56}$$

$$y_{tps} \ge 0, \text{ integer} \qquad \forall t = 1, \ldots, T; \forall p = 1, \ldots, P; \forall s = 1, \ldots, S_p \tag{3.57}$$

$$x_{tps} \in \{0,1\} \qquad \forall t = 1, \ldots, T; \forall p = 1, \ldots, P; \forall s = 1, \ldots, S_p \tag{3.58}$$

$$q_{tbm} \ge 0, \text{ integer} \qquad \forall t = 1, \ldots, T; \forall b = 1, \ldots, B; \forall m = 1, \ldots, M_b \tag{3.59}$$

$$w_{tbm} \in \{0,1\} \qquad \forall t = 1, \ldots, T; \forall b = 1, \ldots, B; \forall m = 1, \ldots, M_b \tag{3.60}$$

$$\varpi \le B, \text{ integer} \tag{3.61}$$

Eq. (3.49) is the asset management objective function that represents the business sales and profit opportunity. It is similar to the net present value of product net profit. However, the part costs are estimated independently for every supplier *s* of part category *p* for product *t*. The objective is to select a supplier *s* for each the part category *p* who will return maximum profit for product type *t*. The first term represents the net present worth of manufacturing and revenue costs. The second term represents the present monetary value of the total parts cost supplied by supplier *s* of part category *p* during the lifetime of product type *t*. Constraint (3.50) ensures that the total number of parts supplied across all suppliers *S* for part category *p* will be equal to the number of parts required to manufacture the total number of whole units for each product type *t*. Constraint (3.51) ensures that the number of parts of category *p* supplied by supplier *s* for each product *t* will not exceed the capacity of supplier *s*. Constraint (3.52) is to ensure that only one supplier *s* will be selected for each part category *p* for product type *t*. Constraint (3.53) ensures that the number of whole units of product type *t* processed by resource *m* will be equal to the demand for product type *t*. Constraint (3.54) ensures that the number of whole units of product type *t* processed by resource *m* will not exceed the capacity of resource *m.* Constraint (3.55) is to ensure that only one resource *m* will be selected for each process step *b* for product type *t*. Constraint (3.56) ensures that the number of whole units of product type *t* required for delivery by delivery courier *d* will not exceed the capacity of delivery courier *d.* Constraint (3.57) are the non-negativity and integrality constraints for number of units of product type *t* processed by resource *m* for every process step *b*. Constraint (3.58) is a binary constraint for product type *t* is processed by resource *m* for process step *b*; 1, product type *t* is processed by resource *m* for process step b; 0, otherwise. Constraint (3.59) are the non-negativity and integrality constraints for number of parts of category p supplied by supplier s. Constraint (3.60) is a binary constraint for part category p for product type t is supplied by supplier s; 1, if part category p for product type t is supplied by supplier s; 0, otherwise. Constraint (3.61) is to insure that the bottle neck process ϖ is either before or at the final process b, and must be an integer.

There are additional parameters the must be further defined. First, U_{tps} is the number of product units of type t manufactured during the product lifecycle ς_{tps} when selecting supplier s of part category p, and is expressed as

$$U_{tps} = \frac{\varsigma_{tps} - \alpha_{tps} - \left(\sum_{t=1}^{T} \sum_{b=1}^{\varpi-1} \sum_{m=1}^{M_b} \beta_{tbm} q_{tbm} w_{tbm} \right)}{\beta_{t\varpi m}}. \tag{3.62}$$

The numerator is the product lifecycle of product t less the responsiveness of supplying one unit from part category p by supplier s and less the total responsiveness of processing product t all the way until before the manufacturing bottleneck process ω-1. The denominator is the responsiveness of processing product t at the bottleneck process ω.

Next, we define Ω_t, which is the sum of sales revenue, manufacturing and delivery costs compounded at end of supplier responsiveness α_{tps} for supplier s of part category p for product type t. It is expressed as

$$\Omega_t = \frac{C_{\varpi m} \left(\theta_t - \sum_{b=1}^{B} \sum_{m=1}^{M_b} a_{tbm} w_{tbm} q_{tbm} - e_{dt} U_t \right) \left((1+\tau)^{U_{tps}} - 1 \right)}{\tau (1+\tau)^{U_{tps}}}, \tag{3.63}$$

where the first term of Eq. (3.63) represents capacity of the manufacturing bottleneck ω multiplied by a bracket that represents the unit sales price of product t, less the total cost of processing one unit of product type t through manufacturing resource m of each process b, and less the cost of delivering one unit of product type t by delivery courier d. The compounding period is the bottleneck responsiveness $\beta_{t\varpi m}$.

$$\eta_{tps} = \frac{\Omega_t}{(1+\tau)^{\alpha_{tps}/\beta_{t\varpi m}}}, \tag{3.64}$$

where η_{tps} is the net present value of Ω_t at time zero. In essence, Eq. (3.64) is the net present value of revenue and manufacturing costs, compounded per bottleneck period $\beta_{t\varpi m}$.

The present value μ_{tps} of the uniform series of part cost for the amount of U_{tps} product units compounded at end of supplier payment lead time ψ_{tps} for supplier s of part category p for product type t, and compounded per bottleneck period $\beta_{t\varpi m}$ is expressed as

$$\mu_{tps} = \frac{C_{\varpi m} \times \left(c_{tps} y_{tps}\right) \times \left((1+\tau)^{U_{tps}} - 1\right)}{\tau(1+\tau)^{U_{tps}}}, \tag{3.65}$$

Finally, the net present value of μ_{tps} at time zero is computed as

$$\xi_{tps} = \frac{\mu_{tps}}{(1+\tau)^{\frac{\psi_{tps}}{\beta_{t\varpi m}} - 1}}. \tag{3.66}$$

Eq. (3.66) represents the net present value of μ_{tps} at time the end of ψ_{tps}, the payment lead time to supplier s of part category p for product type t, less one period pf bottleneck responsiveness $\beta_{t\varpi m}$, and compounded per bottleneck period $\beta_{t\varpi m}$.

Numerical Example for Computing Build-to-Order Supply Chain Global Asset Management Performance

Assume we have a supply chain configuration where manufacturing and delivery has been decided to be Resource m_3, Resource m_6 and Courier d_3, as shown in Figure 3.11. Therefore, the bottleneck process in terms of responsiveness is at Process b_2 = 5 days. Now, if we assume a capacity of m_6 at b_2 = 3 product units, then the bottleneck capacity ($C_{\omega m}$) = 3 product units.

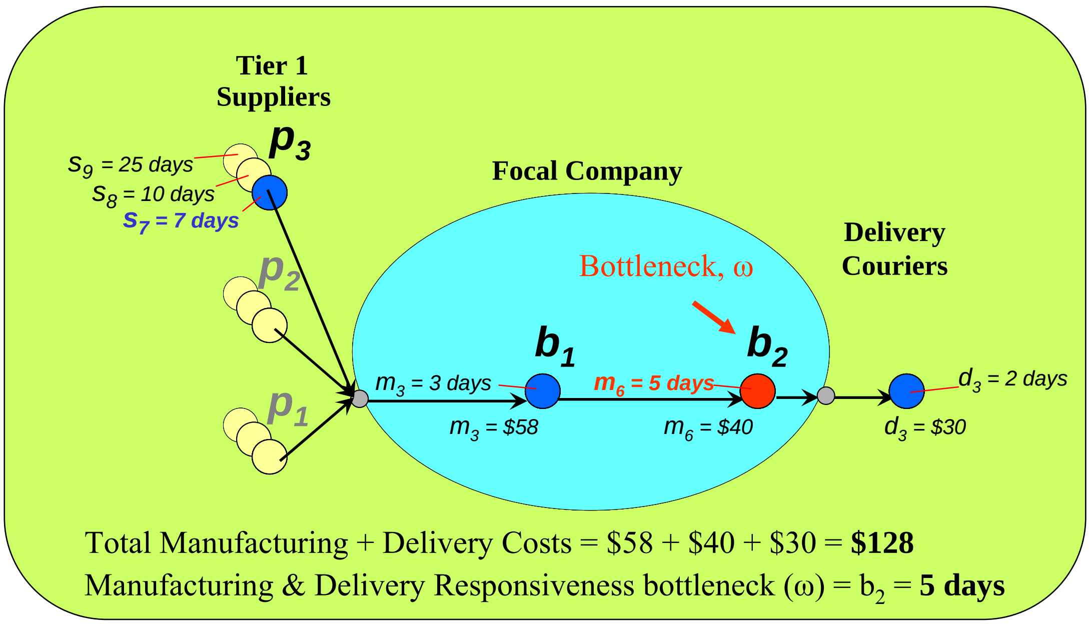


Figure 3.11. Analysis of manufacturing and delivery costs for asset management analysis.

Total manufacturing and delivery costs per product = \$58 + \$40 + \$30 = \$128. Now, suppose we assume the unit sales price (θ_t) of product t is \$1,000 and product lifetime (ς_t) = 1 year (365 days). As shown in Figure 3.12, assume the manufacturing supply chain has three suppliers (s_7, s_8, and s_9) and each is capable of producing Part p_3.

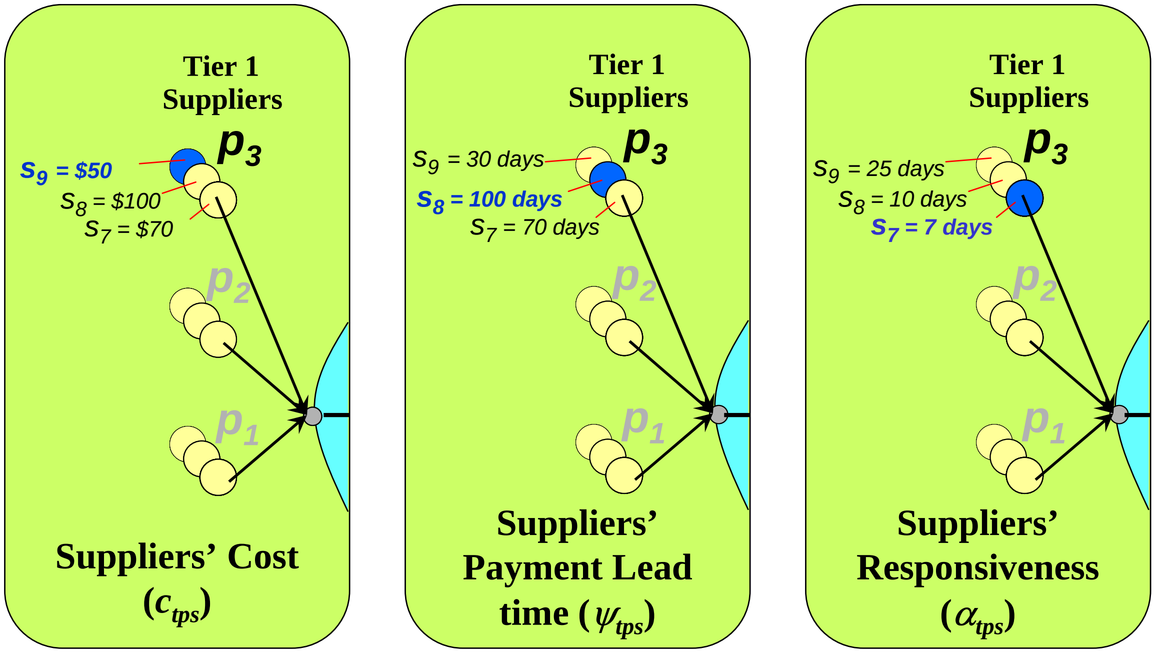


Figure 3.12. Summary of cost, supplier payment lead time and responsive performance measures based on the pool of suppliers of Part p_3.

By analyzing the performance of Suppliers s_7, s_8, and s_9 for supplying Part p_3, each of the three suppliers have *conflicting* performance measures. By conflicting, we mean the best supplier with respect to one performance measure might not necessarily be the best supplier with respect to the other measures. For instance, by only considering the cost and responsiveness performance without considering the part payment lead time to the supplier makes it difficult to decide the best supplier to supply a particular part.

Business Sales and Profit Opportunity Analysis for selecting Supplier s_7:

We are given:

- Manufacturing and delivery bottleneck responsiveness = 5 days
- Bottleneck capacity ($C_{\omega m}$) = 3 product units
- Supplier s_7 payment lead time (ψ_{tps}) = 70 days
- Supplier s_7 Cost (c_{tps}) = $70

- Supplier s_7 Responsiveness (α_{tps}) = 7 days

By substituting into Eq. (3.62), we get

$$U_{tps} = \frac{365-7-3}{5} = 71 \text{ whole product units.}$$

Now, if we assume a discrete compound interest rate, say $\tau = 0.25\%$, then by substituting into Eq. (3.63), we calculate the sum of sales revenue, manufacturing and delivery costs compounded at end of Supplier s_7 responsiveness of seven days for Supplier s_7 for Part p_3 as

$$\Omega_t = \frac{3\times(1{,}000-128)\times\left((1+0.0025)^{71}-1\right)}{0.0025(1+0.0025)^{71}} = \$169{,}991.34.$$

By substituting Ω_t into Eq. (3.64), we get the net present value of Ω_t at time zero for product t as

$$\eta_{tps} = \frac{169{,}991.34}{(1+0.0025)^{\frac{7}{5}}} = \$169{,}398.15.$$

Now, using Eq. (3.65), we compute the net present value of a uniform series of part cost compounded at end of supplier payment lead time 70 days for Supplier s_7 of Part p_3 as

$$\mu_{tps} = \frac{3\times 70\times\left((1+0.0025)^{71}-1\right)}{0.0025(1+0.0025)^{71}} = \$13{,}646.09.$$

Substituting μ_{tps} into Eq. (3.66), we compute the net present value of ξ_{tps} at time zero as

$$\xi_{tps} = \frac{13{,}646.09}{(1+0.0025)^{\frac{70}{5}-1}} = \$13{,}210.25.$$

Finally, using Eq. (3.49), we compute BSPO if Supplier s_7 is selected as 169,398.15 – 13,210.25 = $156,187.89.

Using the above steps, we can compute the Business Sales and Profit Opportunity for both Supplier s_8 and Supplier s_9. Table 3.1, which summarizes the sales and profit opportunity for all three suppliers, should that Supplier s_7 provides the highest BSPO if selected to provide Part p_3 of product t.

Table 3.1. Summary of business sales and profit opportunity for suppliers of Part p_3.

Suppliers for Part p_3	s_7	s_8	s_9
Business Sales and Profit Opportunity	**$156,187.89**	$149,485.59	$150,066.31

In theory and in practice, multiple performance measures in the management of supply chains could be conflicting. For example, a supplier could be more responsive in fulfilling orders by using a relatively expensive method of transportation, *i.e.*, air freight instead of ground shipping, which could lead to an increased cost per unit part supplied, and hence create a tradeoff between responsiveness and cost. Nevertheless, outsourcing a manufacturing process to another country in order to decrease the global supply chain cost might result in a lower global reliability of the supply chain. This creates a tradeoff between cost and reliability. Moreover, flexibility could be increased at a higher cost. In other words, a supplier would increase his finished good inventories and maintain high carrying costs to adapt to any variations in demand from the focal company side, *i.e.*, charge more costs for parts in return for higher flexibility in adapting to order variations.

Nevertheless, solving the supply chain multiobjective global performance measures sequentially is not preferred. For example, if we start by optimizing cost and then try optimizing flexibility, we may end up with a very different solution than if we optimize flexibility first and then cost. Hence, we suggest solving all the performance measures simultaneously.

CHAPTER 4: PROPOSED HEURISTIC SOLUTION PROCEDURES FOR DETERMINISTIC BUILD-TO-ORDER SUPPLY CHAINS

4.1. Introduction

Large industrial supply chains, such as automotive and airplane manufacturers can have more than 1,000 Tier 1 suppliers. For instance, Boeing has about 15,842 suppliers worldwide (Tectura 2005). To illustrate the complexity of supply chain design, consider the following. Suppose that we want to design a build-to-order supply chain for a product that consists of 100 parts. Now, assume that there are five alternative suppliers available for each part, ten manufacturing process steps each with five alternative resources, and three delivery stages with five alternatives. Hence, the total number of possible supply chain configurations that can be formed is 9.63×10^{113}. If we try to enumerate all combinations and if each combination consumes about 3×10^{-6} seconds, then for the abovementioned supply chain, we will need $9.63 \times 10^{113} \times 3 \times 10^{-6} = 2.8889\times10^{73}$ seconds = 9.16×10^{65} years to identify the optimal supply chain configuration. Additionally, if some of the performance measures are not linear, using traditional analytical optimization methods is not advised. Nevertheless, some researchers (*e.g.*, Gokhan *et al.* 2005) use mixed integer programming techniques for optimization based on costs, however, computation times increase exponentially as the problem size increases.

These problem characteristics have motivated supply chain researchers and practitioners to pursue effective heuristic solution approaches that generate near-optimal solutions. Several heuristic approaches such as genetic algorithms (GAs) and tabu search have been used to solve similar problems in traditional supply chains (*e.g.*, Han and Damrongwongsiri 2005; Gokhan *et al.* 2005; Pinto 2004; Farina *et al.* 2003; Jin and Sandhoff 2003; Syarifi *et al.* 2002).

4.2. The Global Supply Chain Performance Heuristic (GSCPH)

In order to be able to address all the abovementioned challenges and still be able to obtain a quick and accurate estimation for a robust supply chain design based on supply chain entity selection, we propose a new heuristic that is similar to the branch and bound method in vertical optimization while using an enhanced horizontal logic for removing the local insignificant performance measures from the calculation of the overall local performance at each stage of the comparison. Hence, the new approach compares supply chain entity performance vertically and horizontally at the same time, as illustrated in Figure 4.1. We name the proposed heuristic the Global Supply Chain Performance Heuristic (GSCPH).

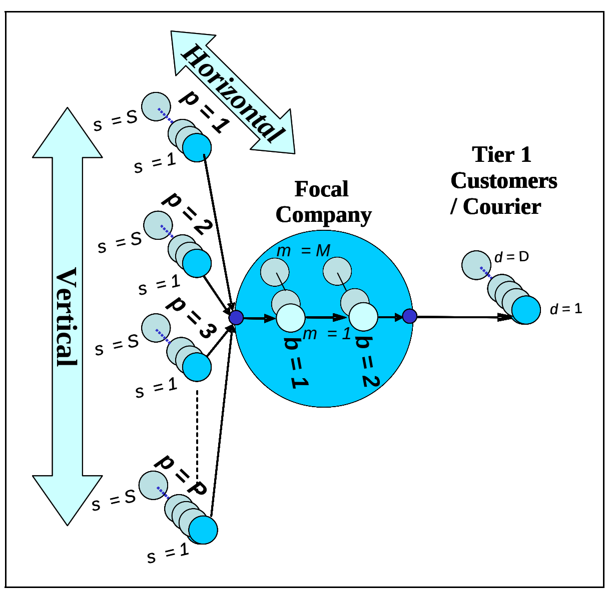


Figure 4.1. Supply chain entity comparison approach in the GSCPH.

4.2.1. Performance Measurement in the GSCPH – The *R*-Ratio

The proposed heuristic aggregates the five performance measures into a single value, *i.e.*, it is not Pareto-optimal-based. Each local performance measure is calculated as a ratio of the best entity within a given pool of supply chain entities. This ratio is referred to as the *R*-Ratio for each local performance measure and $0.0 \leq R\text{-Ratio} \leq 1.0$. The five different ratios are then summed into a single measure that represents the overall global performance of the build-to-order supply chain. Hence, if we have five measures, the highest ΣR-Ratio is equal to five assuming the performance measures are equally-weighted. It is important to note here that the proposed heuristic approach can allow varying weights of performance measures.

4.2.2. The Comparison Strategy in GSCPH

Each local performance measure is compared vertically with respect to the corresponding global measure. This reduces the solution set for every pool of supply chain resources based on the significance of every local performance measure, *i.e.* the maximum *R*-Ratio, for every set of suppliers with respect to the global performance measure. It is worth mentioning that as the number of parts increase in the supply chain, the solution set will decrease as insignificant performance measures will be eliminated from every part, and hence, each performance measure will be considered at one part only, which we refer to as the critical part of the performance measure.

4.2.3. Primary Steps of the GSCPH

The primary steps of the GSCPH are as follows:

1. Within the same part category, a horizontal comparison is performed as shown in Figure 4.1 and the optimal supplier for each performance measure is identified independently of the other measures. These values represent the independent optimal local performance measures for each part category. In other words, these values represent the maximum value that could be achieved for each performance measure among all the resources of a given process or pool of suppliers. Hence, these are the ultimate performance for every performance measure within a pool of resources.
2. For each performance measure, the optimal suppliers for all part categories are compared vertically. The supplier in the pool of suppliers who contributes least to the corresponding independent optimal global performance measure is identified and called the *critical supplier* for that given performance measure. Each of the five independent global performance measures is calculated by quantifying the local independent performance of the supply chain entities along the entire supply chain. The comparison of all the optimal entities for all part categories or parallel operations will help identify the bottleneck entity.
3. Under each performance measure, whenever a critical supplier is identified within a certain part category, the same performance measure is considered for optimization of the suppliers of that part category, while the performance measure is removed from consideration during optimization of suppliers at all the other part categories.

4. The R-Ratio for each supplier of every part category is computed. The ratio represents the supplier performance relative to the optimal supplier performance of that part category. If the control level for the performance measure is minimization, then

$$R\text{-Ratio} = 1 - \left(\frac{\text{supplier } s \text{ performance } - \text{ optimal performance}}{\text{optimal performance}} \right) \tag{4.1}$$
$$= 2 - \left(\frac{\text{supplier } s \text{ performance}}{\text{optimal performance}} \right).$$

If the control level for the performance measure is maximization, then

$$R\text{-Ratio} = \left(\frac{\text{supplier } s \text{ performance}}{\text{optimal performance}} \right). \tag{4.2}$$

5. For every supplier, the summation of all the R-Ratios (ΣR-Ratio) is identified.
6. Under each part category, the supplier with maximum ΣR-Ratio is selected.

Note that if the performance measures are weighted, the weights should be multiplied by the R-Ratios. In this research, we assume the five performance measures have equal weights.

Hence, if, for example, a certain part is needed and its responsiveness is considered the bottleneck as it falls on the critical path of the manufacturing process, then we make use of this fact by not considering this same performance measure for comparison within every pool of resources that is parallel to the given critical process. In other words, suppose we need both Parts A and Part B for assembling. Now, assume the best responsiveness among Part A suppliers is equal to 100 days and the worst responsiveness supplier of Part A is 120 days, while the optimal responsiveness among Part B suppliers is equal to 10 days and the worst supplier responsiveness is equal to 20 days. Then, it can be seen that the responsiveness is an insignificant performance measure in Part *B*, and we should not consider the responsiveness as one of the primary factors when comparing the overall performance of suppliers of Part *B*. This is because the worst supplier responsiveness in Part *B* is still much better than the best responsiveness supplier in Part *A*. The GSCPH removes the responsiveness of suppliers of Part *B* from the multi-objective comparison. Figure 4.3 is the logic flow of the GSCPH.

4.3. Numerical Example for Applying GSCPH for the Build-to-Order Supply Chain

As shown in Figure 4.2, a manufacturing supply chain consists of nine suppliers for three different part categories. Each part category can be produced by any of its three alternative sets of suppliers, *i.e.*,

- Each Supplier s_1, s_2, and s_3 is capable of producing Part p_1.
- Each Suppliers s_4, s_5, and s_6 is capable of producing Part p_2.
- Each Suppliers s_7, s_8, and s_9 is capable of producing Part p_3.

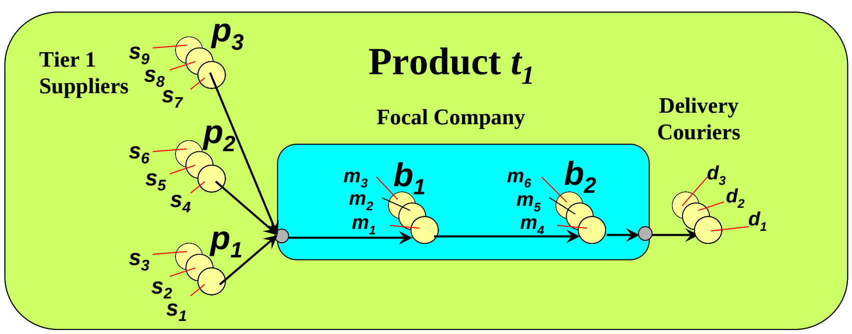


Figure 4.2. Supply chain entities of a manufacturing process

The five performance measures related to each supplier is displayed as shown in Table 4.1.

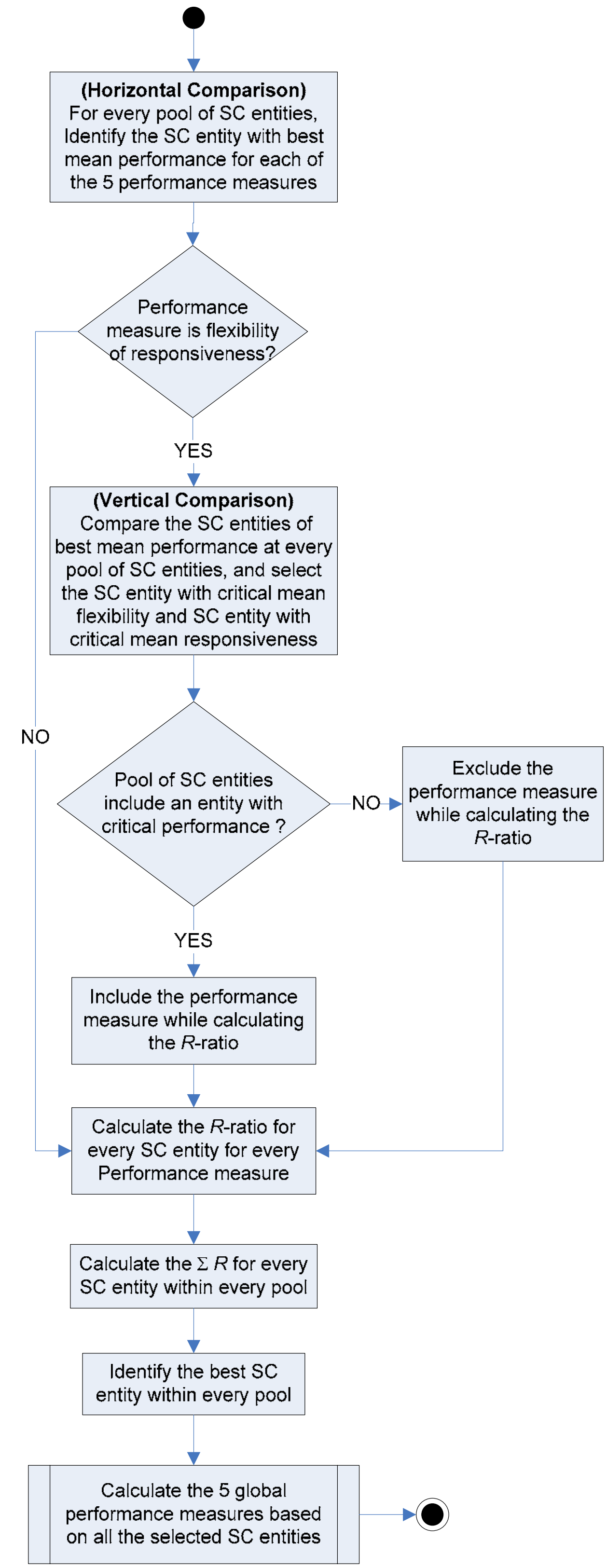


Figure 4.3. Logic flow of the GSCPH.

Table 4.1. Illustrative numerical example of the GSCPH.

		p_3						
		min	max	min	min	max		
		Respons. (days)	Reliability (%)	Flexibility (days)	Cost ($)	Asset Mngt ($)		
Supplier	s_9	25	0.93	1.50	50	-785.52		
	s_8	10	0.91	2.00	100	2417.20		
	s_7	7	0.98	0.70	70	1973.73	Σ R	p_3
	$R\,s_9$	-1.57	0.95	-0.14	1.00	-0.32	-0.90	s_9
	$R\,s_8$	0.57	0.93	-0.86	0.00	1.00	1.57	s_8
	$R\,s_7$	1.00	1.00	1.00	0.60	0.82	**2.42**	s_7

		p_2						
		min	max	min	min	max		
		Respons. (days)	Reliability (%)	Flexibility (days)	Cost ($)	Asset Mngt ($)		
Supplier	s_6	5	0.96	2.00	102	116.54		
	s_5	6	0.97	1.00	100	97.00		
	s_4	9	0.96	1.20	95	118.01	Σ R	p_2
	$R\,s_6$	1.00	0.99	0.00	0.93	0.99	1.91	s_6
	$R\,s_5$	0.80	1.00	1.00	0.95	0.82	2.77	s_5
	$R\,s_4$	0.20	0.99	0.80	1.00	1.00	**2.80**	s_4

		p_1						
		min	max	min	min	max		
		Respons. (days)	Reliability (%)	Flexibility (days)	Cost ($)	Asset Mngt ($)		
Supplier	s_3	5	0.92	0.50	45	80		
	s_2	14	0.93	1.00	70	130		
	s_1	8	0.925	1.30	50	200	Σ R	p_1
	$R\,s_3$	1.00	0.99	1.00	1.00	0.40	2.39	s_3
	$R\,s_2$	-0.80	1.00	0.00	0.44	0.65	2.09	s_2
	$R\,s_1$	0.40	0.99	-0.60	0.89	1.00	**2.88**	s_1

For Part p_1:

Optimal supplier for responsiveness is Supplier s_3.

Optimal supplier for reliability is Supplier s_2.

Optimal supplier for responsiveness is Supplier s_3.

Optimal supplier for flexibility is Supplier s_3.

Optimal supplier for cost is Supplier s_1.

For Part p_2:

Optimal supplier for responsiveness is Supplier s_6.

Optimal supplier for reliability is Supplier s_5.

Optimal supplier for responsiveness is Supplier s_5.

Optimal supplier for flexibility is Supplier s_4.

Optimal supplier for cost is Supplier s_4.

For Part p_3:

Optimal supplier for responsiveness is Supplier s_7.

Optimal supplier for reliability is Supplier s_7.

Optimal supplier for flexibility is Supplier s_7.

Optimal supplier for cost is Supplier s_9.

Optimal supplier for asset management is Supplier s_8.

Identifying the Critical Suppliers:

- The critical supplier for responsiveness is s_7 at Part p_3. Therefore, responsiveness is removed from comparison at Parts p_1 and p_2.
- The critical supplier for reliability is s_7 at Part p_1. Therefore, reliability is removed from comparison at Parts p_2 and p_3.

- The critical supplier for flexibility is s_7 at Part p_2. Therefore, flexibility is removed from comparison at Parts p_1 and p_3.

For Supplier s_9:

R-Ratio(s_9) responsiveness = $2-\left(\frac{25}{7}\right)$ = – 1.57

R-Ratio(s_9) reliability = $\left(\frac{0.93}{0.98}\right)$ = 0.95

R-Ratio(s_9) flexibility = $2-\left(\frac{25}{7}\right)$ = – 0.14

R-Ratio(s_9) reliability and R-Ratio(s_9) flexibility are not considered since they were previously removed from consideration.

R-Ratio(s_9) cost = $2-\left(\frac{25}{7}\right)$ = 1

R-Ratio(s_9) asset management = $\left(\frac{0.93}{0.98}\right)$ = – 0.32

Therefore, ΣR-Ratio(s_9) = – 1.57 + 1 + – 0.32 = – 0.90

Similarly,

$$\Sigma R\text{-Ratio}(s_8) = 0.57 + 0 + 1 = 1.57$$

$$\Sigma R\text{-Ratio}(s_7) = 1 + 0.6 + 0.82 = 2.42$$

Since ΣR-Ratio(s_7) > ΣR-Ratio(s_8), and also ΣR-Ratio(s_7) > ΣR-Ratio(s_9), the Supplier s_7 is the supplier to be selected for Part p_3. Similarly, Supplier s_1 is the supplier to be selected for Part p_1 and Supplier s_4 is the supplier to be selected for Part p_2.

4.4. Implementation of the GSCPH for Experimental Evaluation

The GSCPH and an exact approach are both coded in C. Experiments are run to test the proposed heuristic approach by comparing its output to an exact, exhaustive method. Upper and lower limits are to be chosen by the user for every performance measure at each group category, and are arbitrarily defined in this research. Random values are generated from a uniform distribution bounded between the user-specified upper and lower limits.

Table 4.2 lists 24 different experiments are designed as per the different supply chain configurations. The number of possible supply chain combinations that could be obtained from each experiment is shown in the Iterations column. .For example, Experiment 1 has 12,150 different possible configurations, and so on. The Running Time column is the actual clock time required to evaluate all of the configurations.

Table 4.2. A listing of the designed experiment.

Experiment	Number of Parts	No of Suppliers	No of Suppliers/ Part	Number of Manufacturing Processes	Number of Manufacturing Resources	Number of Manufacturing Resources/ Process	No of Delivery Resources	Exact method		
	P		*S*	*B*		*M*	*D*	Iterations	Running Time	
1	5	15	3	2	10	5	2	12,150	36	Secs
2	5	15	3	2	10	5	5	30,375	1.46	Mins
3	5	15	3	5	25	5	2	1,518,750	1.22	hours
4	5	25	5	2	10	5	2	156,250	7.50	Mins
5	5	25	5	2	10	5	5	390,625	18.75	Mins
6	5	25	5	5	20	4	3	9,600,000	7.68	hours
7	10	30	3	3	9	3	2	3,188,646	2.55	hours
8	10	30	3	3	12	4	3	11,337,408	9.07	hours
9	10	30	3	3	15	5	2	14,762,250	11.81	hours
10	10	30	3	2	10	5	2	2,952,450	2.36	hours
11	10	30	3	4	12	3	4	19,131,876	15.31	hours
12	20	40	2	2	4	2	2	8,388,608	6.71	hours
13	20	40	2	3	6	2	3	25,165,824	20.14	hours
14	25	50	2	1	2	2	1	67,108,864	53.70	hours

Thirty one random replications of each experiment are run to obtain the objective function value. The ΣR-Ratio is compared for both the exact and the heuristic methods, and the results for the first four experiments are summarized in Table 4.3. Recall that the maximum possible ΣR-Ratio for a single supply chain configuration is 5.0.

Table 4.3. Summary of the ΣR-Ratio values for the 31 random replications across the 14 different experiments.

	Experiment 1		Experiment 2		Experiment 3		Experiment 5	
Rep	Exact	Heuristic	Exact	Heuristic	Exact	Heuristic	Exact	Heuristic
1	4.69676	4.52329	4.83005	4.7249	4.68394	4.60333	4.73583	4.6333
2	4.69904	4.63752	4.74468	4.59841	4.7319	4.52332	4.69857	4.50501
3	4.67604	4.67248	4.65537	4.43852	4.74157	4.63731	4.54759	4.52614
4	4.65316	4.60919	4.59692	4.50994	4.69726	4.40391	4.597	4.597
5	4.80765	4.63744	4.6614	4.3023	4.63198	4.38622	4.78185	4.75494
6	4.62568	4.52055	4.65541	4.39066	4.71774	4.53842	4.71664	4.70153
7	4.62392	4.32857	4.70377	4.38178	4.65863	4.48376	4.71792	4.55047
8	4.53988	4.27847	4.73887	4.63292	4.68216	4.47266	4.66124	4.51762
9	4.6846	4.60445	4.73002	4.62669	4.63808	4.51046	4.63922	4.59235
10	4.76812	4.62393	4.59968	4.44233	4.70539	4.57771	4.67315	4.48344
11	4.75926	4.44669	4.59778	4.41175	4.659	4.41109	4.73184	4.66158
12	4.80355	4.60628	4.70093	4.50744	4.61365	4.41261	4.6098	4.48032
13	4.68097	4.49128	4.68877	4.43612	4.65354	4.47811	4.59909	4.51722
14	4.7155	4.57334	4.57736	4.36198	4.74441	4.63348	4.41203	4.34335
15	4.86553	4.75438	4.75872	4.50241	4.7504	4.50859	4.70063	4.54889
16	4.76456	4.6747	4.72298	4.49216	4.6319	4.44396	4.64835	4.61953
17	4.87921	4.8635	4.64271	4.53493	4.71969	4.57131	4.63206	4.5528
18	4.79477	4.67303	4.65965	4.42425	4.71118	4.48927	4.62199	4.54232
19	4.69869	4.40807	4.6836	4.48892	4.7904	4.55872	4.50533	4.28325
20	4.62437	4.40098	4.55242	4.43	4.63929	4.55708	4.59907	4.38355
21	4.80328	4.7061	4.68873	4.52086	4.71413	4.54084	4.70747	4.42996
22	4.77354	4.5364	4.6395	4.31318	4.71463	4.57435	4.72097	4.57582
23	4.58218	4.53459	4.63457	4.48079	4.67338	4.60444	4.61397	4.44968
24	4.78538	4.77765	4.59342	4.31911	4.74417	4.52957	4.75376	4.73916
25	4.81997	4.80145	4.65865	4.57129	4.8098	4.65869	4.66053	4.61305
26	4.72128	4.70244	4.60323	4.2749	4.58062	4.35243	4.79044	4.68468
27	4.7444	4.70007	4.6785	4.6229	4.77643	4.61759	4.59778	4.48784
28	4.62053	4.58901	4.79162	4.68522	4.76202	4.58684	4.79975	4.6436
29	4.67448	4.59723	4.60137	4.47181	4.74958	4.65363	4.73499	4.73499
30	4.73427	4.72677	4.56659	4.36298	4.61609	4.52049	4.68161	4.63926
31	4.77993	4.66728	4.77631	4.69399	4.63952	4.52674	4.53218	4.14691

	Experiment *6*		Experiment *8*		Experiment *9*		Experiment *10*	
Rep	**Exact**	**Heuristic**	**Exact**	**Heuristic**	**Exact**	**Heuristic**	**Exact**	**Heuristic**
1	4.70887	4.66115	4.6655	4.53475	4.74374	4.70392	4.60963	4.38129
2	4.62684	4.50798	4.60121	4.49952	4.74657	4.60495	4.68505	4.67256
3	4.62917	4.39602	4.71015	4.64739	4.74989	4.62843	4.69309	4.5682
4	4.69747	4.39473	4.63452	4.47294	4.79899	4.68647	4.62788	4.35248
5	4.65046	4.44058	4.64477	4.51134	4.63198	4.38622	4.80865	4.71833
6	4.78933	4.72613	4.70207	4.53553	4.77541	4.54905	4.7265	4.64342
7	4.61775	4.58931	4.68708	4.51469	4.70543	4.55134	4.7181	4.52545
8	4.67391	4.34432	4.59387	4.42445	4.70661	4.54513	4.80554	4.71148
9	4.64926	4.38	4.59412	4.46554	4.80597	4.74445	4.73043	4.65697
10	4.71615	4.44244	4.62924	4.48403	4.79502	4.68814	4.59607	4.47754
11	4.60867	4.44866	4.64755	4.41913	4.83748	4.72373	4.72016	4.69628
12	4.70417	4.53557	4.66583	4.5357	4.63337	4.55275	4.74703	4.72506
13	4.75294	4.46045	4.72627	4.55205	4.76115	4.74763	4.76948	4.63627
14	4.53353	4.30863	4.67564	4.6088	4.78408	4.70296	4.77709	4.60137
15	4.6348	4.48896	4.57798	4.4393	4.83046	4.75027	4.72202	4.68435
16	4.57932	4.39611	4.57839	4.34952	4.66978	4.5717	4.75779	4.62321
17	4.51082	4.31523	4.62363	4.46127	4.84298	4.78462	4.62316	4.46169
18	4.66323	4.53843	4.5384	4.34155	4.70933	4.46881	4.6386	4.5417
19	4.61525	4.52151	4.76116	4.62451	4.66411	4.64515	4.64957	4.54911
20	4.65531	4.48572	4.76299	4.627	4.73178	4.63511	4.74899	4.6453
21	4.5996	4.41929	4.62264	4.54956	4.63935	4.46228	4.77223	4.62434
22	4.65959	4.39528	4.65191	4.53909	4.60609	4.47253	4.73582	4.6686
23	4.55599	4.37441	4.76759	4.50642	4.81379	4.81024	4.81111	4.72961
24	4.63811	4.44598	4.66536	4.45515	4.73914	4.70107	4.67163	4.46308
25	4.74199	4.6594	4.63505	4.58032	4.80311	4.79297	4.78222	4.6897
26	4.59353	4.47779	4.61759	4.43726	4.79246	4.71999	4.73131	4.6082
27	4.60935	4.40715	4.59956	4.44497	4.76139	4.73075	4.69089	4.59528
28	4.54636	4.19451	4.66352	4.55144	4.62961	4.53831	4.90931	4.89737
29	4.592	4.48941	4.63632	4.53158	4.70616	4.60868	4.63583	4.51884
30	4.58523	4.47039	4.6369	4.48433	4.7679	4.61913	4.6929	4.5694
31	4.61525	4.2757	4.72067	4.47906	4.75694	4.69622	4.72146	4.62567

	Experiment 11		Experiment 12		Experiment 13		Experiment 14	
Rep	Exact	Heuristic	Exact	Heuristic	Exact	Heuristic	Exact	Heuristic
1	4.72248	4.49813	4.63461	4.60992	4.57319	4.5009	4.66119	4.6344
2	4.73335	4.66215	4.65119	4.58856	4.85808	4.75866	4.79221	4.48302
3	4.82851	4.60283	4.75034	4.74546	4.68693	4.58119	4.69558	4.53004
4	4.63524	4.32442	4.63007	4.47002	4.7971	4.73716	4.75829	4.59973
5	4.79745	4.74207	4.60388	4.53353	4.76433	4.61392	4.77306	4.52309
6	4.82394	4.72543	4.70726	4.50919	4.73257	4.52441	4.77784	4.68427
7	4.77009	4.68508	4.78151	4.40601	4.76334	4.73232	4.7344	4.54394
8	4.70569	4.57687	4.69985	4.58465	4.72786	4.70245	4.78527	4.52921
9	4.78306	4.66377	4.67684	4.50846	4.78219	4.76451	4.57061	4.09428
10	4.7721	4.71549	4.76957	4.73802	4.67704	4.59312	4.67717	4.60683
11	4.69412	4.69412	4.69524	4.67612	4.78454	4.63166	4.69993	4.59027
12	4.81901	4.5721	4.69487	4.62454	4.77382	4.73988	4.72047	4.54522
13	4.69975	4.53608	4.75214	4.68032	4.67887	4.50305	4.70784	4.54845
14	4.71772	4.49147	4.75921	4.69625	4.59757	4.51602	4.7621	4.6425
15	4.64531	4.50371	4.72883	4.48409	4.75927	4.70919	4.70878	4.57081
16	4.85998	4.85998	4.74427	4.67232	4.67069	4.50988	4.80902	4.52305
17	4.78559	4.73831	4.61943	4.50136	4.73748	4.66101	4.78595	4.50226
18	4.8287	4.52944	4.86079	4.8444	4.78244	4.70321	4.80433	4.46823
19	4.67414	4.34158	4.79701	4.56138	4.73333	4.55503	4.74425	4.58972
20	4.70132	4.50371	4.63369	4.56604	4.7351	4.70209	4.65272	4.60842
21	4.78977	4.57674	4.72781	4.55738	4.73551	4.67591	4.69949	4.641
22	4.65672	4.55684	4.71911	4.68953	4.66129	4.58008	4.74685	4.60219
23	4.70893	4.59757	4.74276	4.50463	4.80937	4.66654	4.80245	4.79253
24	4.59081	4.37013	4.81376	4.76964	4.66806	4.57589	4.77889	4.59666
25	4.80722	4.72458	4.66497	4.53239	4.68582	4.50291	4.68832	4.6258
26	4.63469	4.43809	4.77417	4.76108	4.78214	4.51326	4.78267	4.64451
27	4.7645	4.61991	4.72327	4.63318	4.84268	4.79977	4.69511	4.59327
28	4.74506	4.55256	4.70768	4.6729	4.86091	4.80059	4.7323	4.68726
29	4.72476	4.53115	4.72639	4.60502	4.71322	4.66547	4.75636	4.67732
30	4.8036	4.63861	4.71883	4.54935	4.71258	4.5348	4.64915	4.22112
31	4.70261	4.59414	4.73602	4.62729	4.68999	4.60165	4.73456	4.47363

The absolute average deviation and the variance of the heuristic compared to the exact solution for each experiment are shown in Table 4.4 and these results are summarized graphically in Figure 4.4. “E” means ΣR-Ratio value generated by the exact method and “H” means the ΣR-Ratio value generated by the proposed heuristic method.

Table 4.4. Summary of the average deviation and variance for the 14 experiments.

Experiment	Number of Parts	No of Suppliers	No of Suppliers/ Part	Number of Manufacturing Processes	Number of Manufacturing Resources	Number of Manufacturing Resources/ Process	No of Delivery Resources	Average Deviation	Variance	Average Deviation	Variance	Exact method		
	P		S	B		M	D	Abs(E-H)		Abs(E-H)/E		Iterations	Running Time	
1	5	15	3	2	10	5	2	0.120431	0.008735	0.025569	0.0003986	12,150	36	Secs
2	5	15	3	2	10	5	5	0.186392	0.006967	0.039985	0.000324	30,375	1.46	Mins
3	5	15	3	5	25	5	2	0.168244	0.003397	0.035829	0.0001548	1,518,750	1.22	hours
4	5	25	5	2	10	5	2	0.112358	0.007856	0.024188	0.0003715	156,250	7.50	Mins
5	5	25	5	2	10	5	5	0.185904	0.007616	0.040118	0.0003539	390,625	18.75	Mins
6	5	25	5	5	20	4	3	0.149332	0.002688	0.032089	0.0001228	9,600,000	7.68	hours
7	10	30	3	3	9	3	2	0.100551	0.004204	0.021284	0.0001914	3,188,646	2.55	hours
8	10	30	3	3	12	4	3	0.111206	0.0038	0.023649	0.0001763	11,337,408	9.07	hours
9	10	30	3	3	15	5	2	0.10067	0.003935	0.021283	0.0001753	14,762,250	11.81	hours
10	10	30	3	2	10	5	2	0.132132	0.007782	0.027875	0.0003512	2,952,450	2.36	hours
11	10	30	3	4	12	3	4	0.107817	0.007412	0.022846	0.0003278	19,131,876	15.31	hours
12	20	40	2	2	4	2	2	0.088709	0.00506	0.018365	0.0002155	8,388,608	6.71	hours
13	20	40	2	3	6	2	3	0.015135	0.001593	#DIV/0!	#DIV/0!	25,165,824	20.14	hours
14	25	50	2	1	2	2	1	0.063114	0.00514	0.012976	0.0002164	67,108,864	53.70	hours

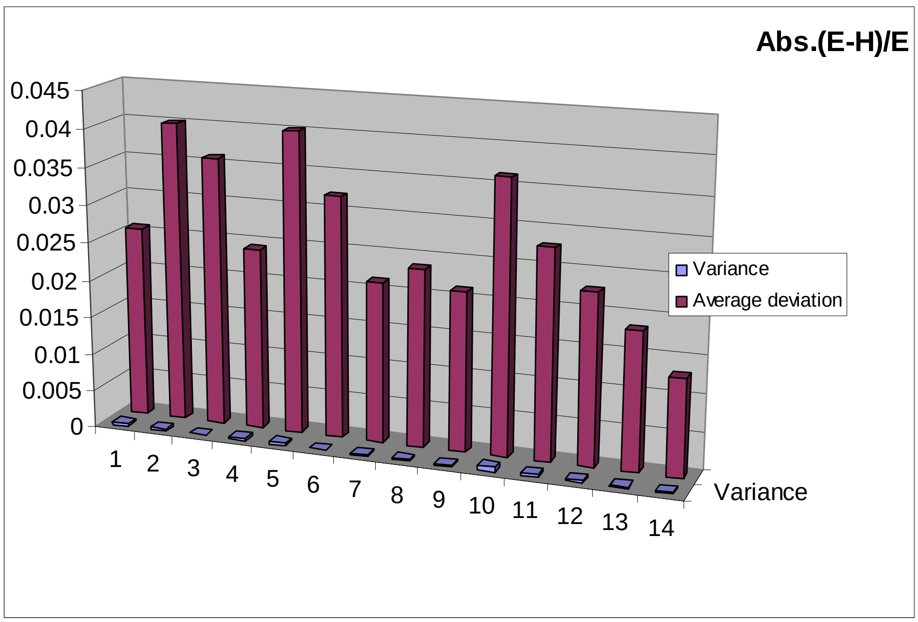


Figure 4.4. Results of absolute average deviation and variance for the 14 experiments.

It can be seen from the results that the maximum absolute average deviation obtained in any experiment is less than 4%, while the relevant maximum variation obtained in any experiment is consistently less than 0.5%. Hence, based on the obtained results for the experiments, the GSCPH approach can provide near-optimal design configurations for build-to-order supply chains.

CHAPTER 5: PROPOSED HEURISTIC SOLUTION PROCEDURES FOR STOCHASTIC BUILD-TO-ORDER SUPPLY CHAINS

5.1. Introduction

In real world, the local performance measures are stochastic and not deterministic as we assume in CHAPTER 4. This chapter is dedicated to studying the performance of the proposed heuristic for designing a supply chain based on the five global performance measures under stochastic conditions. In this case, it is assumed that the local performance measures of supply chain entities follow certain known distributions. The heuristic approach discussed in Chapter 4 is modified to account for variability. Also, simulation experiments are conducted to test the impact of variation in local performance of supply chain entities on the variation of global performance of the build-to-order supply chain network.

5.2. Generating Build-to-Order Supply Chain Designs Using Stochastic Performance Measures

Similar to the deterministic model, the mean value of each of the five local performance measures (flexibility, reliability, responsiveness, cost and asset management). The mean performance of each performance measure is provided as an input to the model. In addition, the following parameters are provided as input to GSCPH for the stochastic case:

- Percent tolerance (π%) for reliability, flexibility, cost, and responsiveness of suppliers, manufacturing resources and delivery couriers (user-specified); and

- The maximum allowable standard deviation ($\sigma_{allowable}$) for each local performance measure of every supply chain entity from the focal company perspective (user-specified).

We name the modified heuristic GSCPH-s. A flowchart for the HGSP is presented in Figure 5.1.

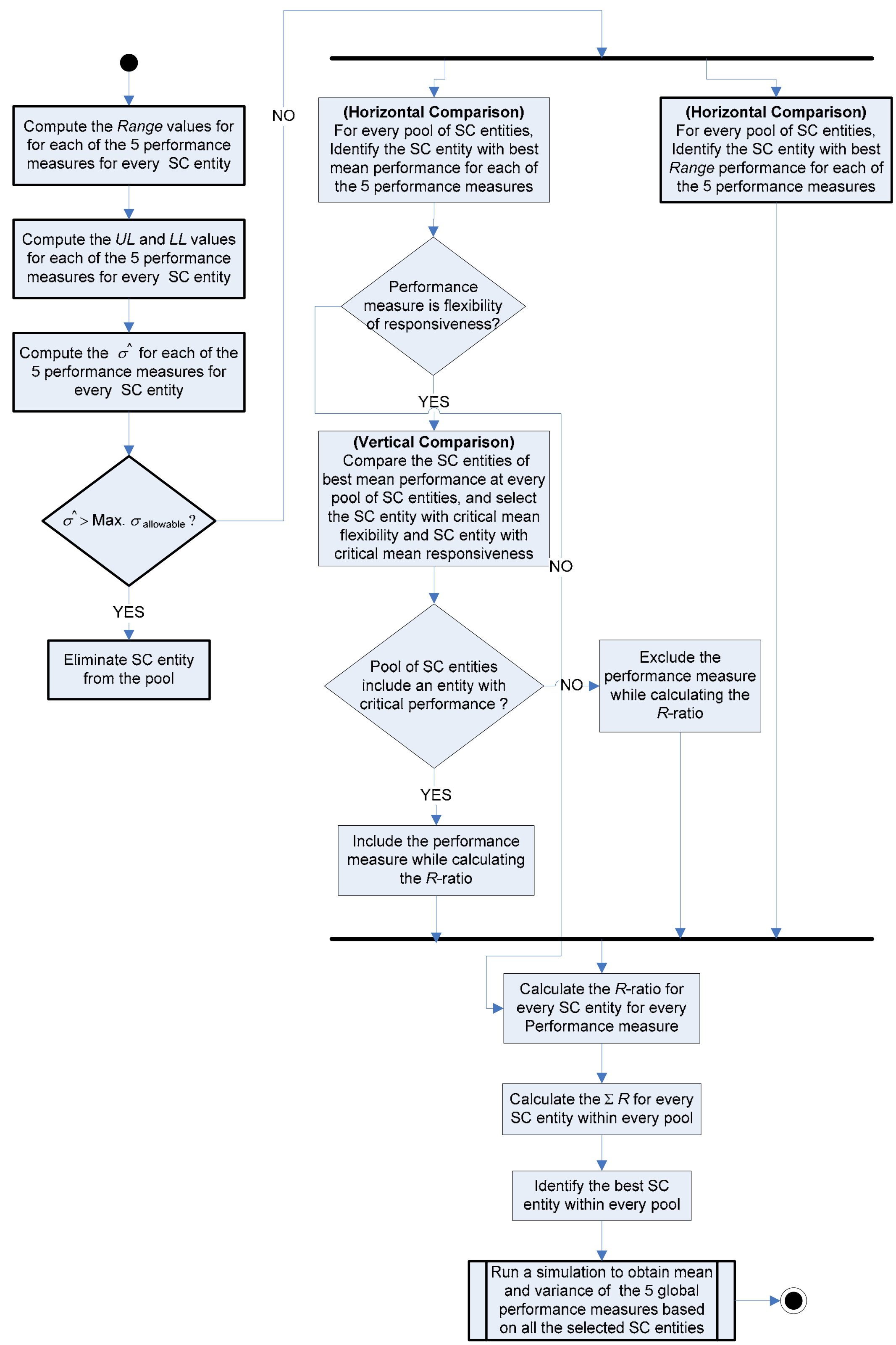


Figure 5.1. Logic flow of the GSCPH-s.

As shown in Figure 5.1, the GSCPH is modified for the stochastic modeling by adding some steps to the GSCPH as follows:

1. The Range is computed for each local performance measure for every supply chain entity as

$$\text{Range} = 2\pi\bar{x}, \tag{5.1}$$

where

π: Percent tolerance of mean performance (*i.e.*, tolerance = $\pm\pi$%).

$\bar{x}$: mean value of the performance measure.

2. The upper limit (UL_i) and the lower limit (LL_i) is computed for each performance measure of each supply chain entity *i* as

$$UL_i = \bar{x}(1 + \pi/100) \tag{5.2}$$

$$LL_i = \bar{x}(1 - \pi/100) \tag{5.3}$$

3. The point estimate for every supply chain entity's standard deviation ($\hat{\sigma}$) is estimated for each performance measure as

$$\hat{\sigma} = \text{Range}/4 \tag{5.4}$$

This estimate is similar to that suggested Mendenhall and Sincich (1995).

4. An elimination constraint is enforced, where a supply chain entity is eliminated if the estimated standard deviation of a performance measure is greater than the user-specified maximum allowable standard deviation, *i.e.*, if $\hat{\sigma} > \sigma_{allowable}$ for the performance measure.

5. Within the same part category, a horizontal comparison is performed similar to that of GSCPH, and the best supplier for each performance measure is identified

independently of the other measures. These values represent the best local performance measures at each part category.

6. For each performance measure, the optimal suppliers for all part categories are compared vertically. The one among the best suppliers who contributes least to the independent global performance measure is identified and called the critical supplier for that given performance measure. Each of the five independent global performance measures is calculated by quantifying the local independent performance of the supply chain entities along the entire supply chain, *i.e.,* for every performance measure at every pool, identify the supply chain entity with best mean (x^{**}), and the supply chain entity with minimum Range (x^{*}).
7. For every performance measure at every pool of entities, the *R*-Ratio representing the relative performance of the remaining supply chain entities are calculated using Eq. (4.1) and Eq. (4.2).
8. Calculate the Mean *R*-Ratio for all supply chain entities' mean within a pool: *R*-Ratio = 2 – ($\overline{x}/\overline{x}^{**}$), for the minimization case, or R = ($\overline{x}/\overline{x}^{**}$) for the maximization case.
9. Calculate the Range *R*-Ratio for the all other supply chain entities' range within a pool = 2 – (Range of $\overline{x}$ / Range of $\overline{x}^{*}$).
10. The Combined *R*-Ratio for each supply chain entity = (Mean *R*-Ratio + Range *R*-Ratio)/2.
11. Identify the optimal supply chain entity for each performance measure as the one with the highest Combined *R*-Ratio.

12. After identifying the best supply chain entity for each performance measure at every pool, apply the previous steps of the GSCPH to identify the best supply chain entity at each pool similar to the previous procedure described in CHAPTER 4.

5.3. Stochastic Modeling Assumptions

Some assumptions are made for the stochastic performance of suppliers.

- All supply chain entity performance follows a normal probability distribution function. This assumption is made for the general model because the actual distribution of all performance measures are unknown and may vary from one product to the other Since the deterministic mean performance is known for each performance measure at every supply chain entity, we assume the stochastic performance may follow a normal probability distribution. The mean of the normal probability distribution is equal to the deterministic performance value that varies with several standard deviations following a normal probability distribution for each performance measure and at every supply chain entity.
- The maximum allowable variation for any supply chain entity or process performance is specified as an input by the focal company.
- The mean of the supply chain entities performance is known with a tolerance of ± 10%. However, any level of tolerance can be specified.
- The level of significance (α) = 5 %.

5.4. Numerical Example Applying GSCPH-s to the Build-to-Order Supply Chain

Figure 5.2 shows a manufacturing supply chain that consists of nine suppliers for three different part categories. The five performance measures related to each supplier are shown in Table 5.1. Each part category can be produced by any of its three alternative sets of suppliers, *i.e.*,

- Each Supplier s_1, s_2, and s_3 is capable of producing Part p_1.
- Each Supplier s_4, s_5, and s_6 is capable of producing Part p_2.
- Each Supplier s_7, s_8, and s_9 is capable of producing Part p_3.

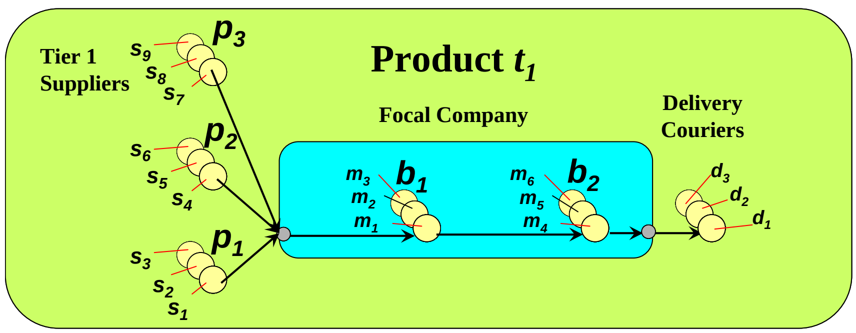


Figure 5.2. Example manufacturing supply chain to illustrate GSCPH-s.

Table 5.1. Numerical example to illustrate GSCPH-s.

	p_3											
	min		max		min		min		max			
	Respons. (days)		Reliability (%)		Flexibility (days)		Cost ($)		Asset Mngt ($)			
Supplier	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range		
s_9	25	5.0	0.93	0.19	1.50	0.30	50	10	-785.52	157		
s_8	10	2.0	0.91	0.18	2.00	0.40	100	20	2417.20	483		
s_7	7	1.4	0.98	0.20	0.70	0.14	70	14	1973.73	395		
Rs_9	-1.57	-1.57	0.95	0.98	-0.14	-0.14	1.00	1.00	-0.32	1.00		
Rs_8	0.57	0.57	0.93	1.00	-0.86	-0.86	0.00	0.00	1.00	-1.08		
Rs_7	1.00	1.00	1.00	0.92	1.00	1.00	0.60	0.60	0.82	-0.51	Σ R	p_3
ΣRs_9	-1.57		0.96				1.00		0.34		0.73	s_9
ΣRs_8	0.57		0.96				0.00		-0.04		1.50	s_8
ΣRs_7	1.00		0.96				0.60		0.15		**2.71**	**S_7**

	p_2											
	min		max		min		min		max			
	Respons. (days)		Reliability (%)		Flexibility (days)		Cost ($)		Asset Mngt ($)			
Supplier	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range		
s_6	5	1.0	0.96	0.192	2.00	0.40	102	20	116.54	23		
s_5	6	1.2	0.97	0.194	1.00	0.20	100	20	97.00	19		
s_4	9	1.8	0.96	0.192	1.20	0.24	95	19	118.01	24		
Rs_6	1.00	1.00	0.99	1.00	0.00	0.00	0.93	0.93	0.99	0.80		
Rs_5	0.80	0.80	1.00	0.99	1.00	1.00	0.95	0.95	0.82	1.00		
Rs_4	0.20	0.20	0.99	1.00	0.80	0.80	1.00	1.00	1.00	0.78	Σ R	p_2
ΣRs_6			0.99		0.00		0.93		0.89		2.81	s_6
ΣRs_5			0.99		1.00		0.95		0.91		**3.85**	**S_5**
ΣRs_4			0.99		0.80		1.00		0.89		3.69	s_4

	p_1											
	min		max		min		min		max			
	Respons. (days)		Reliability (%)		Flexibility (days)		Cost ($)		Asset Mngt ($)			
Supplier	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range		
s_3	5	1.0	0.92	0.184	0.50	0.10	45	9	80	16		
s_2	14	2.8	0.93	0.186	1.00	0.20	70	14	130	26		
s_1	8	1.6	0.925	0.185	1.30	0.26	50	10	200	40		
Rs_3	1.00	1.00	0.99	1.00	1.00	1.00	1.00	1.00	0.40	1.00		
Rs_2	-0.80	-0.80	1.00	0.99	0.00	0.00	0.44	0.44	0.65	0.38		
Rs_1	0.40	0.40	0.99	1.00	-0.60	-0.60	0.89	0.89	1.00	-0.50	Σ R	p_1
ΣRs_3			1.00				1.00		0.70		**2.70**	**S_3**
ΣRs_2			1.00				0.44		0.51		1.95	s_2
ΣRs_1			1.00				0.89		0.25		2.13	s_1

For Part p_1:

Optimal supplier for responsiveness mean value is Supplier s_3.

Best supplier for responsiveness range is Supplier s_3.

Best supplier for reliability mean value is Supplier s_2.

Best supplier for reliability range is Supplier s_3.

Best supplier for flexibility mean value is Supplier s_3.

Best supplier for flexibility range is Supplier s_3.

Best supplier for cost mean value is Supplier s_3.

Best supplier for cost range is Supplier s_3.

Best supplier for asset management mean value is Supplier s_1.

Best supplier for asset management range is Supplier s_3.

For Part p_2:

Best supplier for responsiveness mean value is Supplier s_6.

Best supplier for responsiveness range is Supplier s_6.

Best supplier for reliability mean value is Supplier s_5.

Best supplier for reliability range is Supplier s_6.

Best supplier for flexibility mean value is Supplier s_5.

Best supplier for flexibility range is Supplier s_5.

Best supplier for cost mean value is Supplier s_4.

Best supplier for cost range is Supplier s_4.

Best supplier for asset management mean value is Supplier s_4.

Best supplier for asset management range is Supplier s_5.

For Part p_3:

Best supplier for responsiveness mean value is Supplier s_7.

Best supplier for responsiveness range is Supplier s_7.

Best supplier for reliability mean value is Supplier s_7.

Best supplier for reliability range is Supplier s_8.

Best supplier for flexibility mean value is Supplier s_7.

Best supplier for flexibility range is Supplier s_7.

Best supplier for cost mean value is Supplier s_9.

Best supplier for cost range is Supplier s_9.

Best supplier for asset management mean value is Supplier s_8.

Best supplier for asset management range is Supplier s_9.

Bottleneck Suppliers (*i.e.* best in part category, bottleneck in general performance):

The bottleneck supplier for responsiveness is s_7 at Part p_3.

LL for responsiveness at s_7 = 7- (1.4/2) = 6.3

UL for responsiveness at s_6 = 5 + (1.0/2) = 5.5

UL for responsiveness at s_3 = 5 + (1.0/2) = 5.5

The LL for responsiveness at s_7 = 6.3 > UL for responsiveness at s_6 and s_3. Therefore, supplier responsiveness performance is removed from horizontal comparison for the other parts (p_1 and p_2) because the responsiveness performance of the suppliers at the other part categories will always be better. Therefore, their performance does not impact the global responsiveness.

The critical supplier for flexibility is s_5 at Part p_2.

LL for flexibility at s_5 = 1.0 – (0.20/2) = 0.9

UL for flexibility at s_7 = 0.70 + (0.14/2) = 0.77

UL for flexibility at s_3 = 0.5 + (0.1/2) = 0.55

$\therefore$ The LL for responsiveness at s_5 = 0.9 > UL for flexibility at s_7 and s_3

$\therefore$ Flexibility performance is removed from horizontal comparison at the other parts (p_1 and p_3) because the flexibility performance of the suppliers at the other part categories will always be better. Therefore, their performance does not impact the global responsiveness.

For Supplier s_9:

R-Ratio(s_9) responsiveness mean = $2-\left(\frac{25}{7}\right) = -1.57$

R-Ratio(s_9) responsiveness range = $2-\left(\frac{5.0}{1.4}\right) = -1.57$

R-Ratio(s_9) reliability mean = $\left(\frac{0.93}{0.98}\right) = 0.95$

R-Ratio(s_9) reliability range = $2-\left(\frac{0.19}{0.18}\right) = 0.98$

R-Ratio(s_9) flexibility mean = $2-\left(\frac{1.5}{0.7}\right) = -0.14$

R-Ratio(s_9) flexibility range = $2-\left(\frac{0.3}{0.14}\right) = -0.14$

R-Ratio(s_9) flexibility is not considered since it was previously eliminated.

R-Ratio(s_9) cost mean = $2-\left(\frac{50}{50}\right) = 1$

R-Ratio(s_9) cost range = $2-\left(\frac{10}{10}\right) = 1$

R-Ratio(s_9) asset management mean = $\left(\frac{-785.52}{2417.20}\right) = -0.32$

R-Ratio(s_9) asset management range = $2-\left(\frac{157}{157}\right)=1.0$

ΣR-Ratio(s_9) responsiveness = (R-Ratio(s_9) responsiveness mean + R-Ratio(s_9) responsiveness range)/2 = -1.57

ΣR-Ratio(s_9) reliability = (R-Ratio(s_9) reliability mean + R-Ratio(s_9) reliability range)/2 = 0.96

ΣR-Ratio(s_9) cost = (R-Ratio(s_9) cost mean + R-Ratio(s_9) cost range)/2 = 1.0

ΣR-Ratio(s_9) Asset Mgt. = (R-Ratio(s_9) Asset Mgt. mean + R-Ratio(s_9) Asset Mgt. range)/2 = 0.34

$\therefore$ ΣR-Ratio(s_9) = – 1.57 + 0.96 + 1 + 0.34 = 0.73

Similarly,

$$\Sigma R\text{-Ratio}(s_8) = 0.57 + 0.96 + 0.00 - 0.04 = 1.50$$

$$\Sigma R\text{-Ratio}(s_7) = 1.0 + 0.96 + 0.60 + 0.15 = 2.71$$

Since ΣR-Ratio(s_7) > ΣR-Ratio(s_8), and also ΣR-Ratio(s_7) > ΣR-Ratio(s_9), then Supplier s_7 is the supplier to be selected for Part p_3. Similarly, as shown in Figure 5.3, Supplier s_3 is the supplier to be selected for Part p_1 and Supplier s_5 is the supplier to be selected for Part p_2.

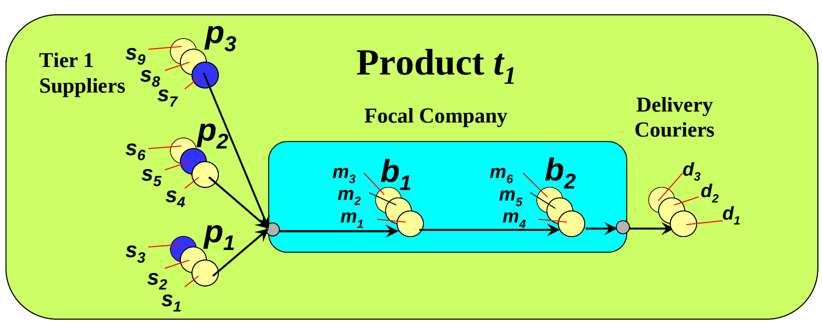


Figure 5.3. Best supply chain supplier configuration.

5.5. Evaluation of the Stochastic Global Performance Measures of the BOSC

5.5.1. Comparing Best Obtained Deterministic Configuration to Best obtained Stochastic Configuration

We now test hypotheses regarding the performance of the GSCPH versus GSCPH-s.

H_0: When using the GSCPH-s method, optimization based on mean and variance will produce a different build-to-order supply chain configuration than in case of using GSCPH-s method.

H_1: When using the GSCPH-s method, optimization based on mean and variance will NOT produce a different build-to-order supply chain configuration than in case of using GSCPH-s method.

Experimental Steps:

1. Randomly generate means and variances for the local performance measures of all build-to-order supply chain entities.
2. Apply the GSCPH approach to obtain the best deterministic build-to-order supply chain configuration based on the mean only.
3. Apply the GSCPH-s approach to obtain the best stochastic build-to-order supply chain configuration based on the mean and variance for the same random values of the mean used in Step 2. An input variability of $\pm\ \pi$=10% tolerance is introduced to the model

4. Repeat the experiment for 30 times, each using different random values for mean and variances of performance measures of build-to-order supply chain entities.
5. Record the output configuration and calculate the percent difference in configuration as shown in Eq. (5.5).

$$\% \text{ diff} = \frac{\text{number of different entities in a stochastic configuration}}{\text{total number of entities in the BOSC}} \tag{5.5}$$

Experiment 1

Both the GSCPH and the GSCPH-s methods are used to identify the best configuration of a build-to-order supply chain of a manufacturing product consisting of five part types, two consecutive manufacturing process steps and a Tier 1 delivery courier. The percent difference between the deterministic and stochastic build-to-order supply chain configurations is calculated for each of the 30 experiments. The results are plotted in Figure 5.4.

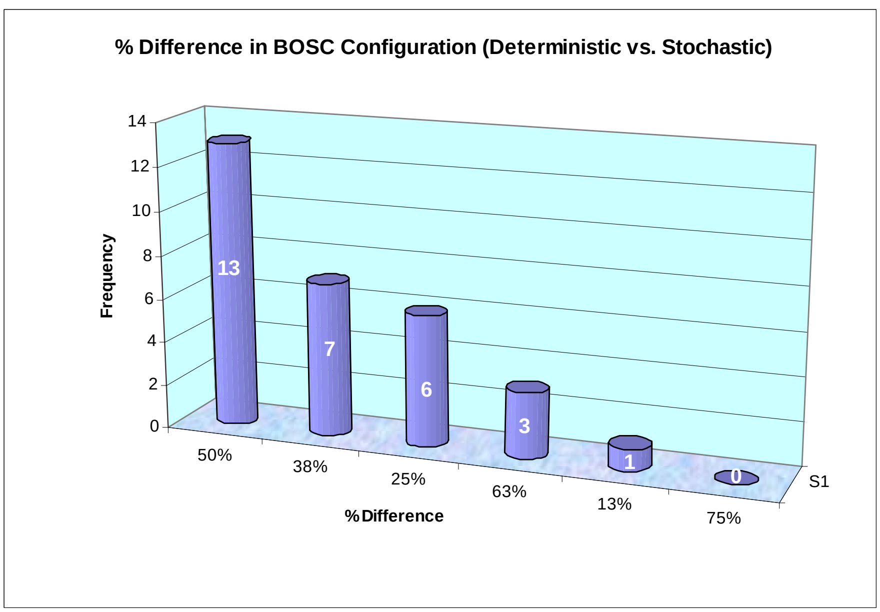


Figure 5.4. Analysis of percent difference in different build-to-order supply chain configurations generated.

Figure 5.4 shows that 13 (of 30) experiments show that GSCPH-s produced configurations that had 50% difference in design than the configurations generated from GSCPH. Seven experiments resulted in a 38% difference in design, six experiments result in a 25% difference in design, and so on. Hence, it can be seen that in 20 experiments, the introduction of variation to the local performance measures resulted in causing at least 25% difference in BOSC configuration at every experiment. It is also noted that each of the 30 experiments showed at least a 13% difference in configuration, where none of the experiments showed identical best configurations under both stochastic and deterministic conditions.

5.5.2. Analyzing the Global Performance Measures Independently

By analyzing the global Performance measures independently, we can infer the relationship between local percent tolerance and each global performance measure.

H_0: Global performance increases when the local percent tolerance in mean performance increases.

H_1: Global performance increases when the local percent tolerance in mean performances does NOT increase.

Experiment 1:

The computation of global performance measures is carried out as follows:

1. Generate values from normal probability distributions based on $\bar{x}$ and $\hat{\sigma}$ for each performance measure at every selected entity within each stage of the build-to-order supply chain.

2. Specify a desired percent tolerance in the mean performance measures.
3. Check whether the generated random value is within the user-specified tolerance, *i.e.* bounded between UL and LL for the supply chain entities' performance at every step. Otherwise, perform truncation of the unbounded generated values.
4. Calculate the global performance values for the BOSC configuration based on the generated data using same procedure in CHAPTER 4.
5. Iterate the random sampling experiment 1,000 times and compute the five global performance measures at each run.
6. Calculate $\bar{x}$ and s of the performance values from 1,000 iterations at every 10% increment in tolerance of local mean performance measure at all supply chain entities.
7. Plot the percent allowable tolerance value as the y-axis and the global mean performance as the x-axis for each performance measure.
8. Plot the performance measure for the 1,000 runs at each percent tolerance on the same graph.

Experiment 2:

1. Perform 1,000 runs every 10% increase in tolerance of local mean responsiveness.
2. The percent tolerance in all other performance measures is 0% at every supply chain entity.

The resulting values are shown in Figure 5.5.

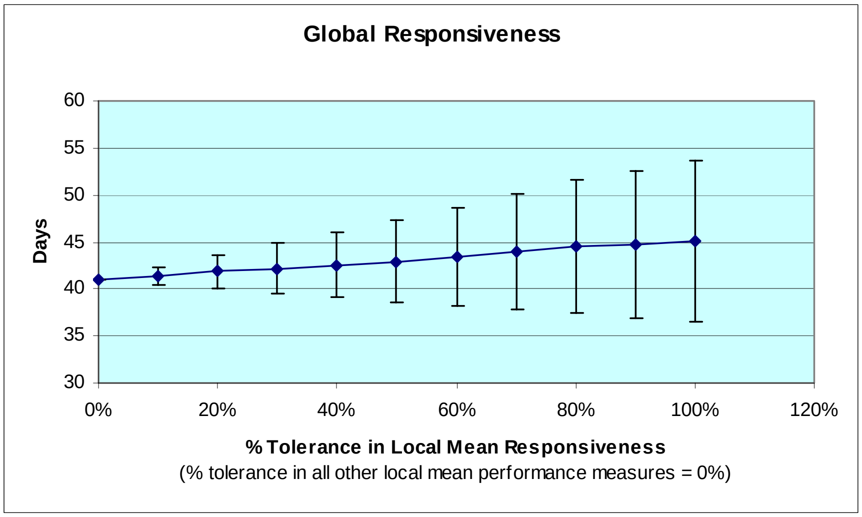


Figure 5.5. Behavior of global mean responsiveness when other tolerances = 0%

Experiment 3:

1. Perform 1,000 runs every 10% increase in tolerance of local mean responsiveness.
2. The percent tolerance in all other performance measures is 10% at every supply chain entity.

The resulting values are shown in Figure 5.6.

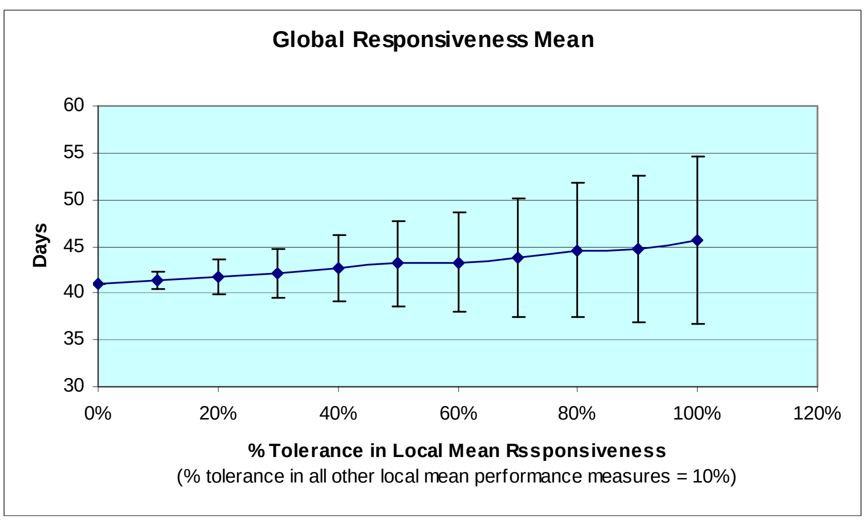


Figure 5.6. Behavior of global mean responsiveness when other tolerances = 10%.

Experiment 4:

1. Perform 1,000 runs every 10% increase in tolerance of local mean responsiveness.
2. The percent tolerance in all other performance measures is 30% at every supply chain entity.

The resulting values are shown in Figure 5.7.

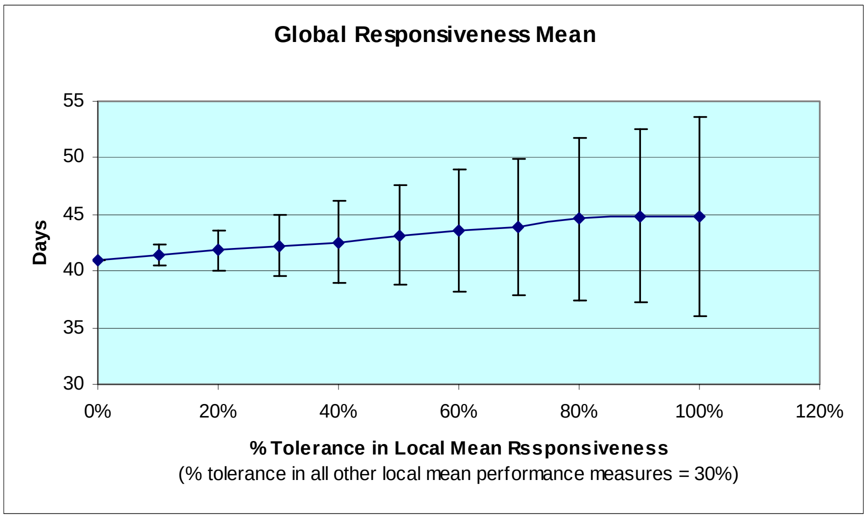


Figure 5.7. Behavior of global mean responsiveness when other tolerances = 30%

Experiment 5:

1. Perform 1,000 runs every 10% increase in tolerance of local mean responsiveness.
2. The percent tolerance in all other performance measures is 80% at every supply chain entity.

The resulting values are shown in Figure 5.8.

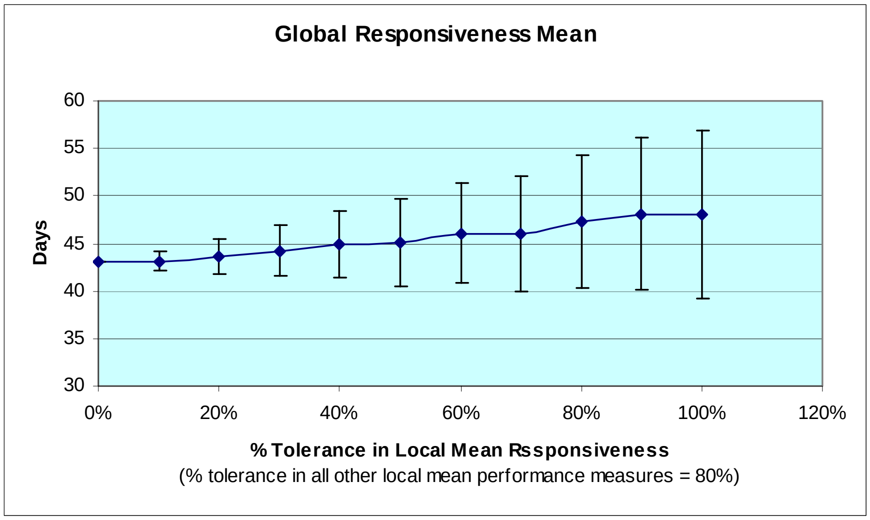


Figure 5.8. Behavior of global mean responsiveness when other tolerances = 80%.

Experiment 6:

1. Perform 1,000 runs every 10% increase in tolerance of all local mean performance measures.
2. Plot the resulting global mean responsiveness at every 10% increase in tolerance.

The resulting values are shown in Figure 5.9.

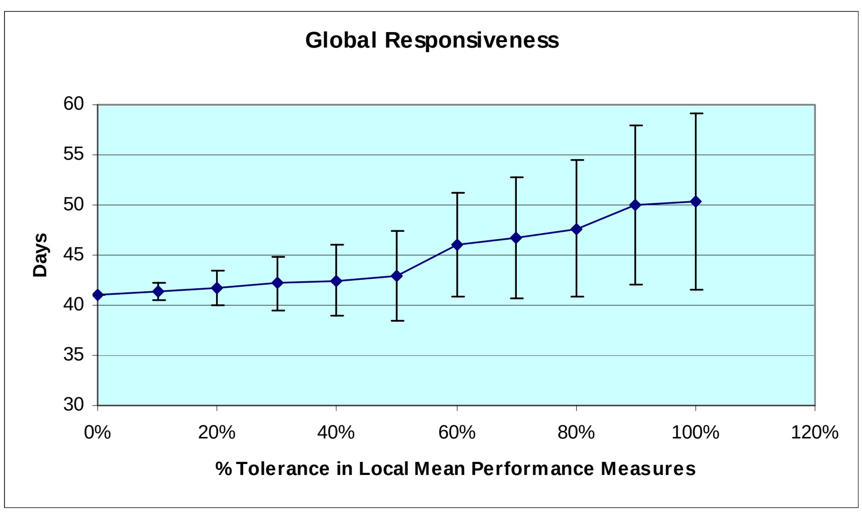


Figure 5.9. Behavior of global mean responsiveness when all tolerances increment by 10%

Experiment 7:

1. Perform 1,000 runs every 10% increase in tolerance of local mean reliability.
2. The percent tolerance in all other performance measures is 0% at every supply chain entity.

The resulting values are shown in Figure 5.10.

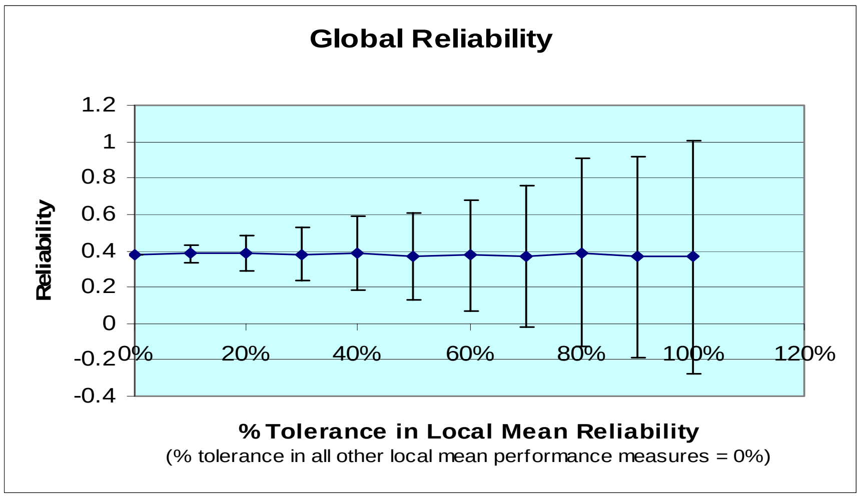


Figure 5.10. Behavior of global mean reliability when other tolerances = 0%

Experiment 8:

1. Perform 1,000 runs every 10% increase in tolerance of local mean reliability.
2. The percent tolerance in all other performance measures is 10% at every supply chain entity.

The resulting values are shown in Figure 5.11.

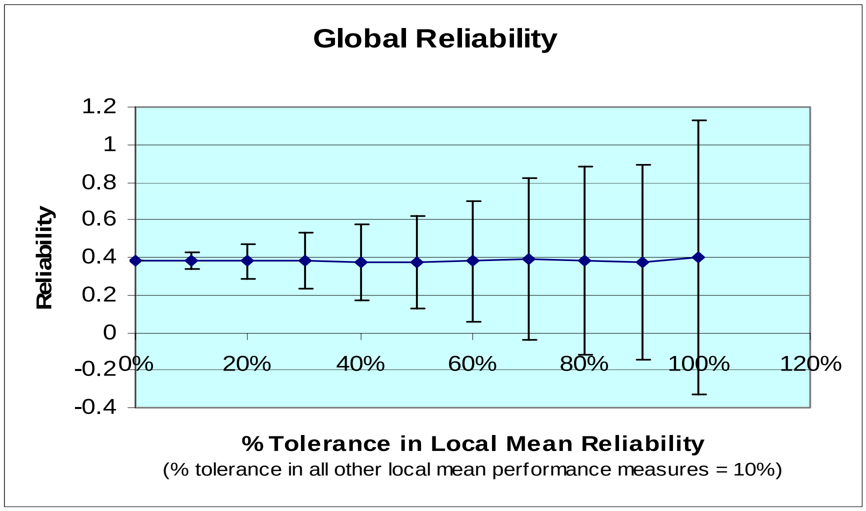


Figure 5.11. Behavior of global mean reliability when other tolerances = 10%.

Experiment 9:

1. Perform 1,000 runs every 10% increase in tolerance of local mean reliability.
2. The percent tolerance in all other performance measures is 30% at every supply chain entity.

The resulting values are shown in Figure 5.12.

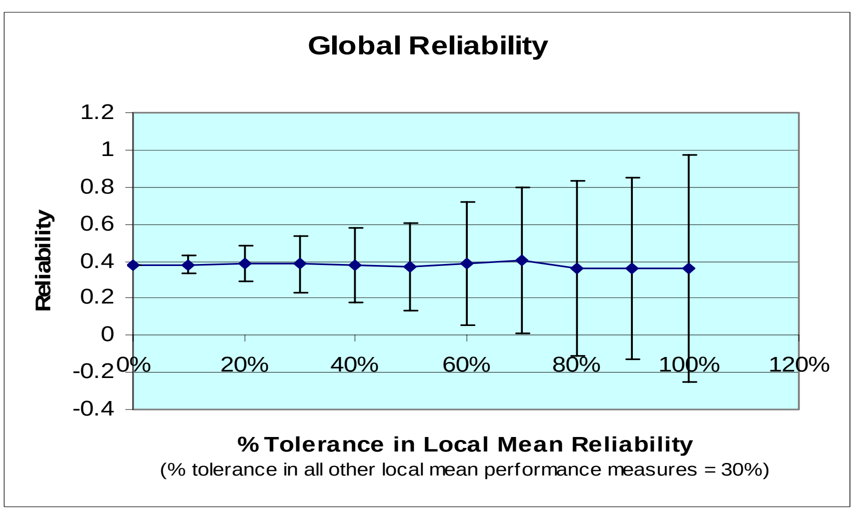


Figure 5.12. Behavior of global mean reliability when other tolerances = 30%.

Experiment 10:

1. Perform 1,000 runs every 10% increase in tolerance of local mean reliability.
2. The percent tolerance in all other performance measures is 80% at every supply chain entity.

The resulting values are shown in Figure 5.13.

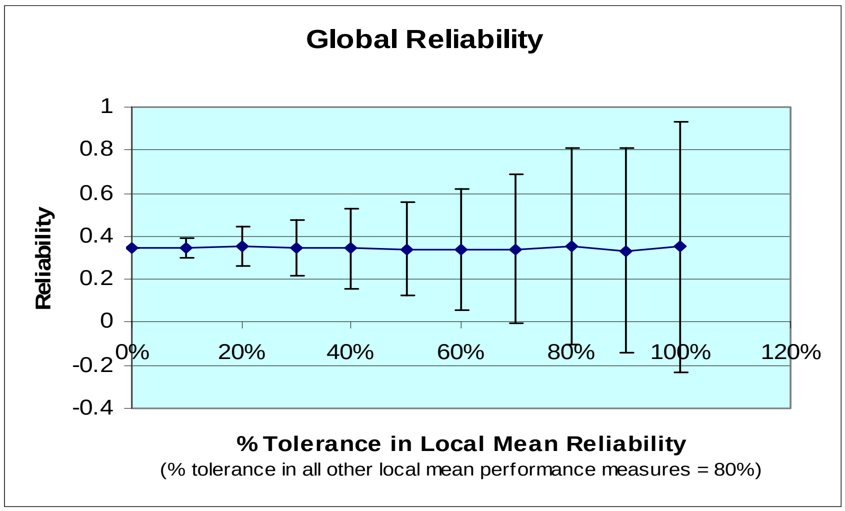


Figure 5.13. Behavior of global mean reliability when other tolerances = 80%.

Experiment 11:

1. Perform 1,000 runs every 10% increase in tolerance of all local mean performance measures.
2. Plot the resulting global mean reliability at every 10% increase in tolerance.

The resulting values are shown in Figure 5.14.

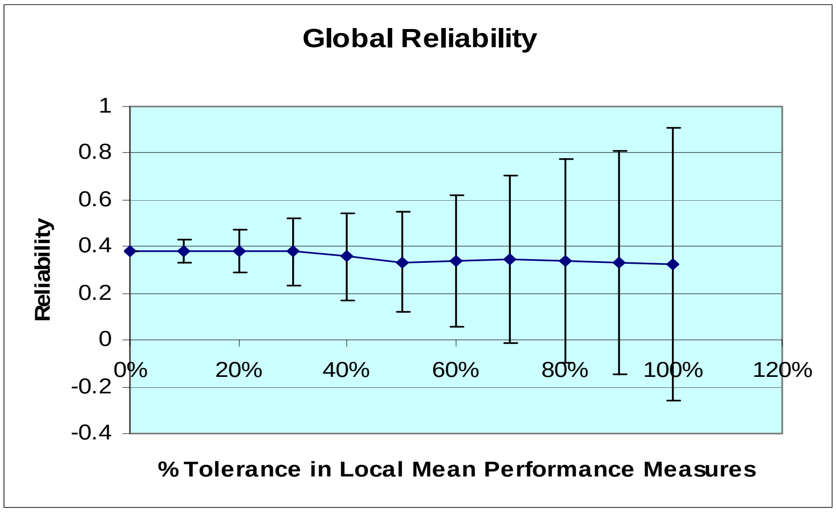


Figure 5.14. Behavior of global mean reliability when all tolerances increment by 10%.

Experiment 12:

1. Perform 1,000 runs every 10% increase in tolerance of local mean flexibility.
2. The percent tolerance in all other performance measures is 0% at every supply chain entity.

The resulting values are shown in Figure 5.15.

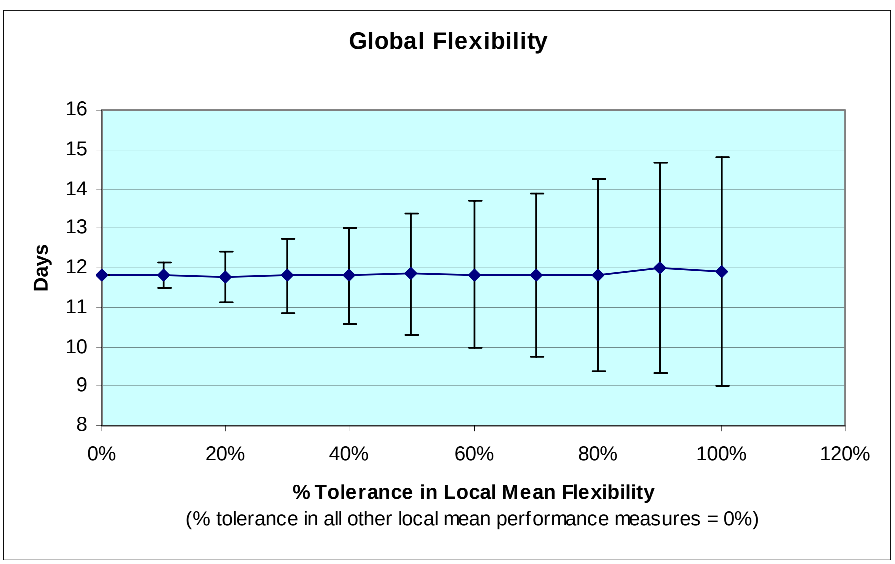


Figure 5.15. Behavior of global mean flexibility when other tolerances = 0%.

Experiment 13:

1. Perform 1,000 runs every 10% increase in tolerance of local mean flexibility.
2. The percent tolerance in all other performance measures is 10% at every supply chain entity.

The resulting values are shown in Figure 5.16.

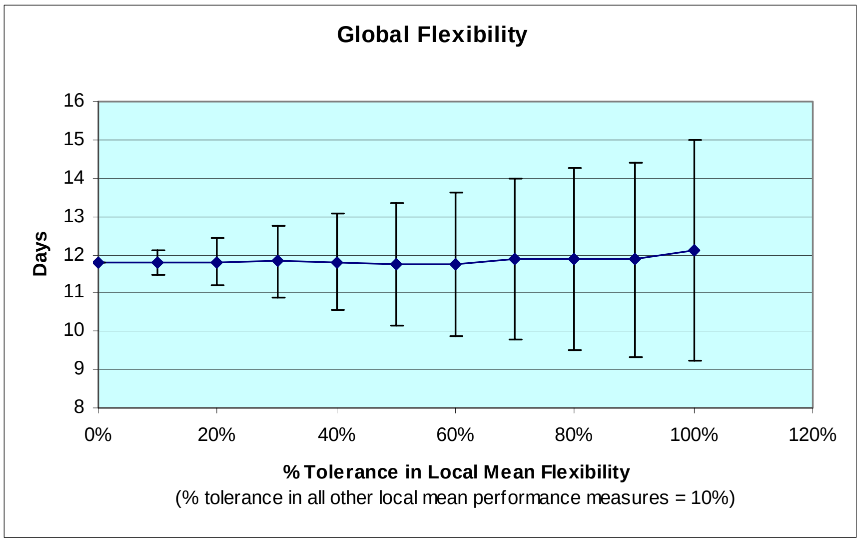


Figure 5.16. Behavior of global mean flexibility when other tolerances = 10%.

Experiment 14:

1. Perform 1,000 runs every 10% increase in tolerance of local mean flexibility.
2. The percent tolerance in all other performance measures is 30% at every supply chain entity.

The resulting values are shown in Figure 5.17.

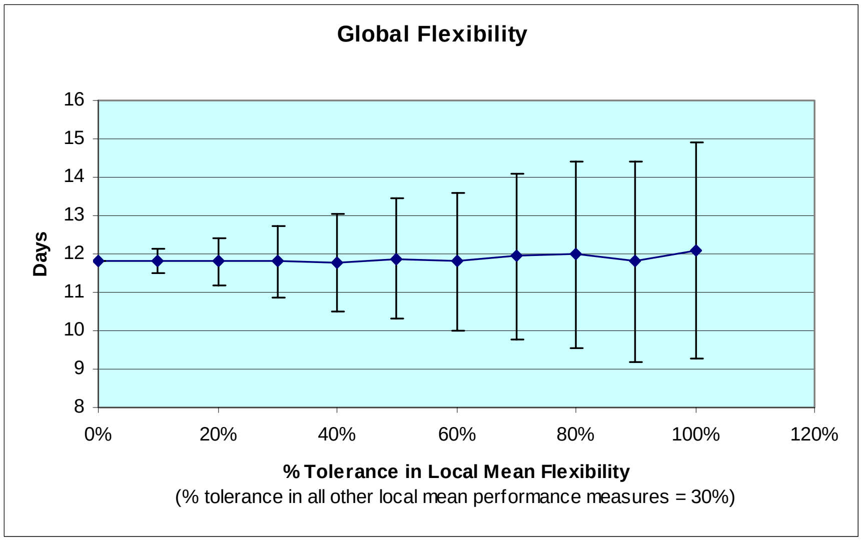


Figure 5.17. Behavior of global mean flexibility when other tolerances = 30%.

Experiment 15:

1. Perform 1,000 runs every 10% increase in tolerance of local mean flexibility.
2. The percent tolerance in all other performance measures is 80% at every supply chain entity.

The resulting values are shown in Figure 5.18.

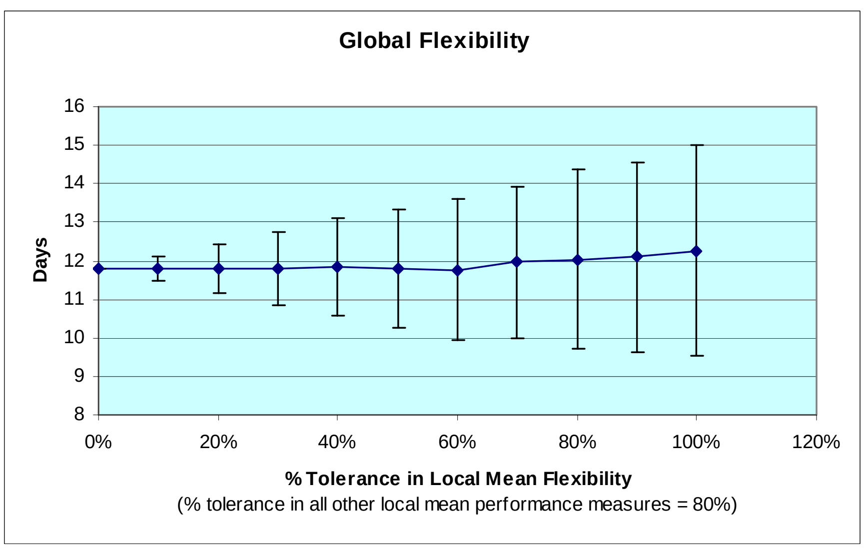


Figure 5.18. Behavior of global mean flexibility when other tolerances = 80%.

Experiment 16:

1. Perform 1,000 runs every 10% increase in tolerance of all local mean performance measures.
2. Plot the resulting global mean flexibility at every 10% increase in tolerance.

The resulting values are shown in Figure 5.19.

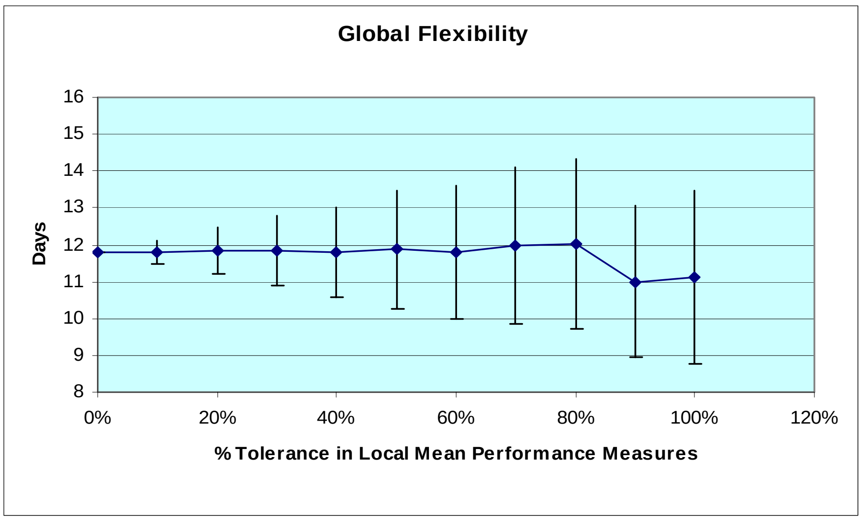


Figure 5.19. Behavior of global mean flexibility when all tolerances increment by 10%.

Experiment 17:

1. Perform 1,000 runs every 10% increase in tolerance of local mean cost.
2. The percent tolerance in all other performance measures is 0% at every supply chain entity.

The resulting values are shown in Figure 5.20.

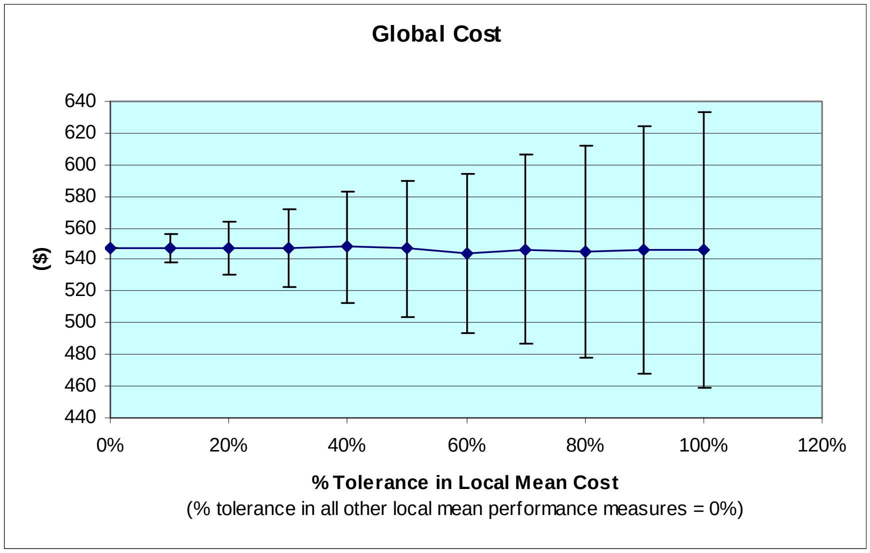


Figure 5.20. Behavior of global mean cost when other tolerances = 0%.

Experiment 18:

1. Perform 1,000 runs every 10% increase in tolerance of local mean cost.
2. The percent tolerance in all other performance measures is 10% at every supply chain entity.

The resulting values are shown in Figure 5.21.

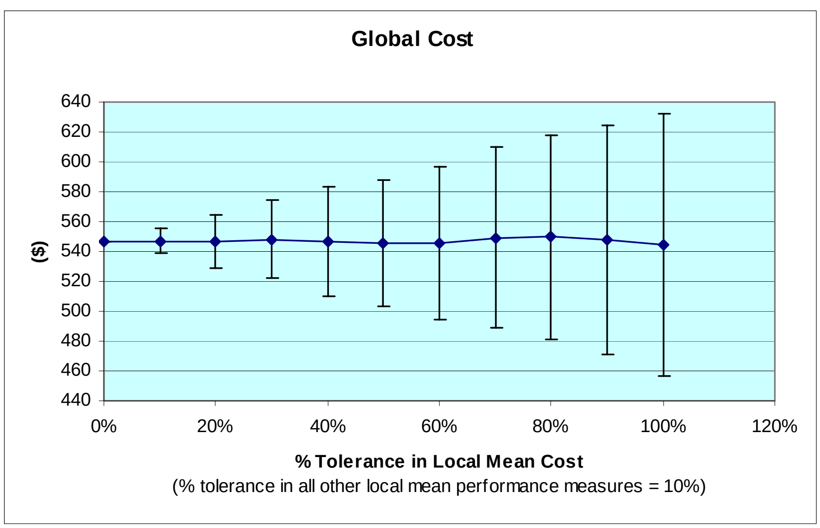


Figure 5.21. Behavior of global mean cost when other tolerances = 10%.

Experiment 19:

1. Perform 1,000 runs every 10% increase in tolerance of local mean cost.
2. The percent tolerance in all other performance measures is 30% at every supply chain entity.

The resulting values are shown in Figure 5.22.

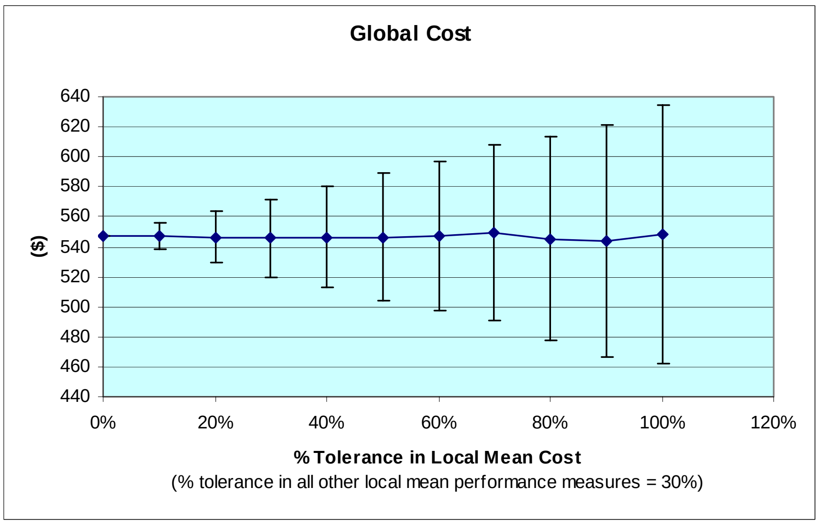


Figure 5.22. Behavior of global mean cost when other tolerances = 30%.

Experiment 20:

1. Perform 1,000 runs every 10% increase in tolerance of local mean cost.
2. The percent tolerance in all other performance measures is 80% at every supply chain entity.

The resulting values are shown in Figure 5.23.

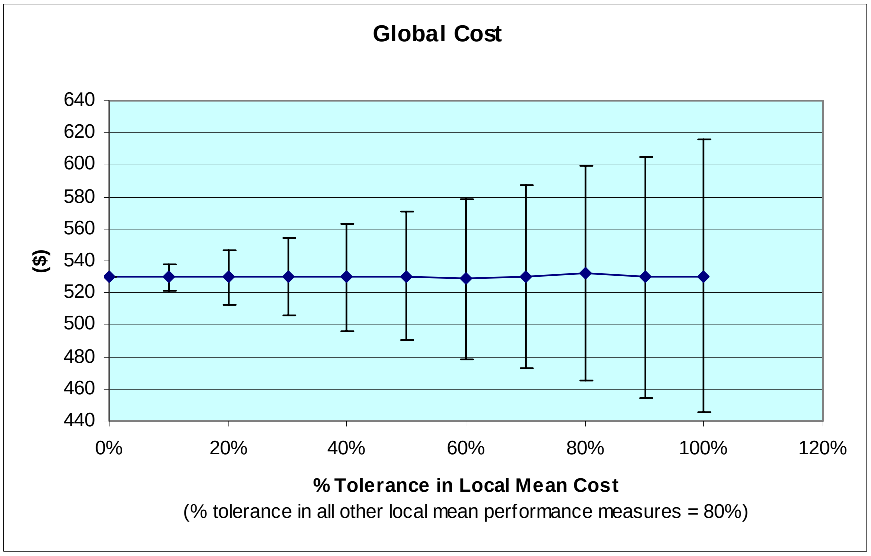


Figure 5.23. Behavior of global mean cost when other tolerances = 80%.

Experiment 21:

1. Perform 1,000 runs every 10% increase in tolerance of all local mean performance measures.
2. Plot the resulting global mean cost at every 10% increase in tolerance.

The resulting values are shown in Figure 5.24.

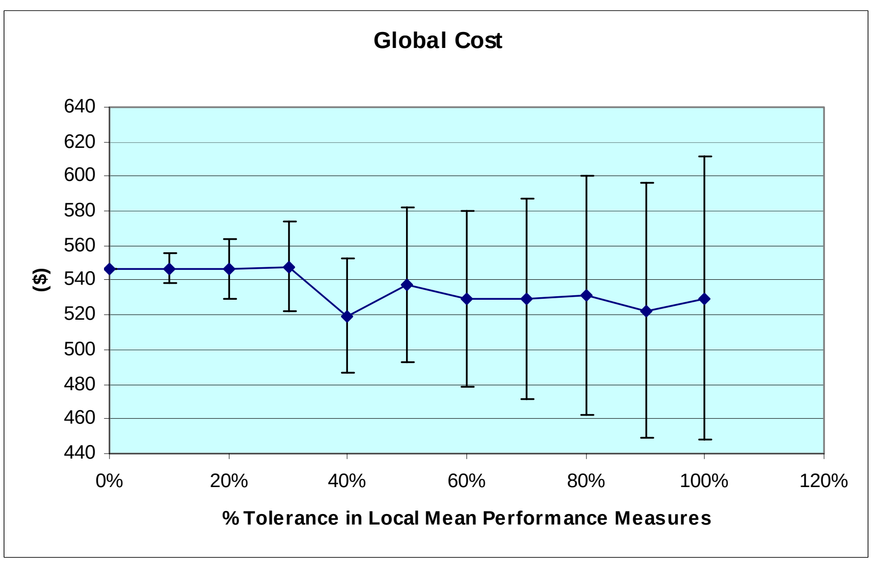


Figure 5.24. Behavior of global mean cost when all tolerances increment by 10%.

Experiment 22:

1. Perform 1,000 runs every 10% increase in tolerance of local mean assets.
2. The percent tolerance in all other performance measures is 0% at every supply chain entity.

The resulting values are shown in Figure 5.25.

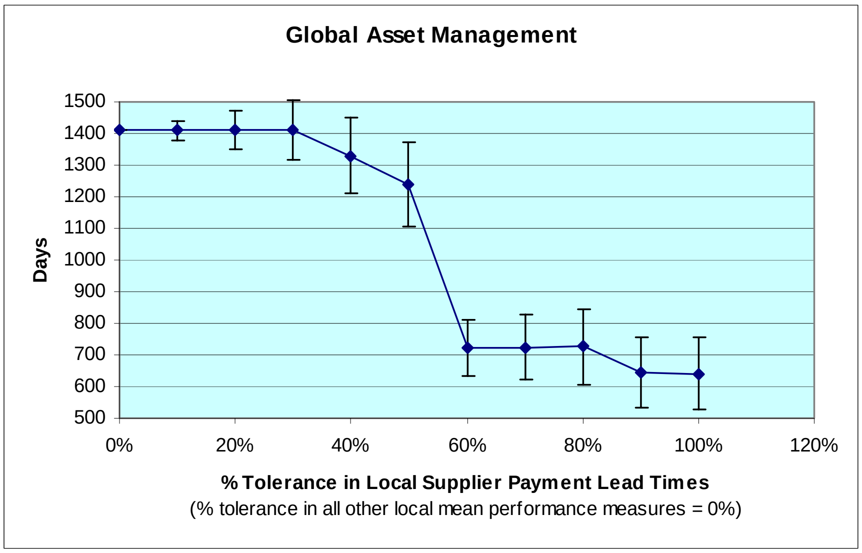


Figure 5.25. Behavior of global mean asset management when other tolerances = 0%.

Experiment 23:

1. Perform 1,000 runs every 10% increase in tolerance of local mean asset management.
2. The percent tolerance in all other performance measures is 10% at every supply chain entity.

The resulting values are shown in Figure 5.26.

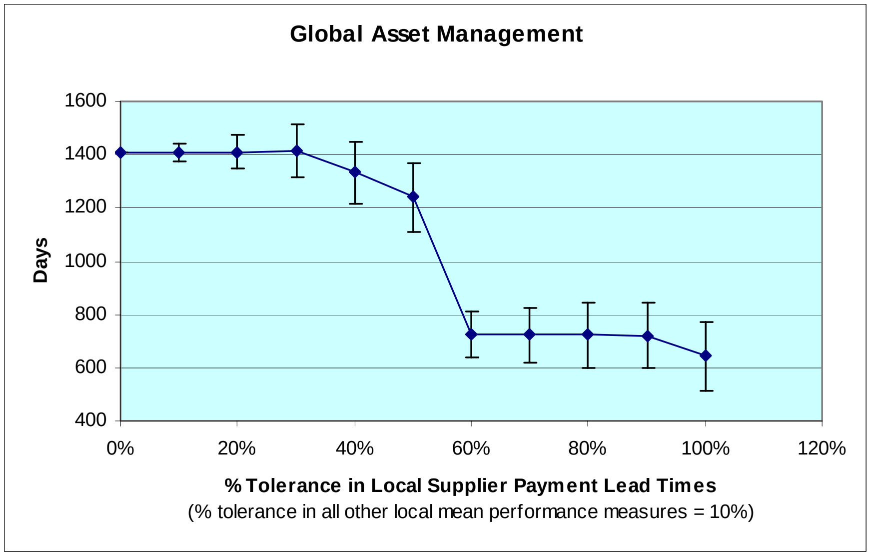


Figure 5.26. Behavior of global mean asset management when other tolerances = 10%.

Experiment 24:

1. Perform 1000 runs every 10% increase in tolerance of local mean asset management.
2. The percent tolerance in all other performance measures is 30% at every supply chain entity.

The resulting values are shown in Figure 5.27.

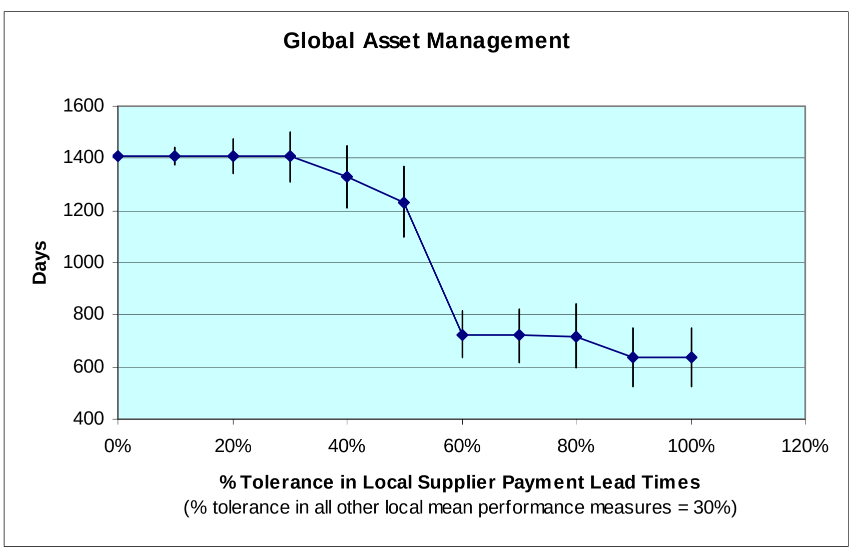


Figure 5.27. Behavior of global mean asset management when other tolerances = 30%.

Experiment 25:

1. Perform 1,000 runs every 10% increase in tolerance of local mean asset management.
2. The percent tolerance in all other performance measures is 80% at every supply chain entity.

The resulting values are shown in Figure 5.28.

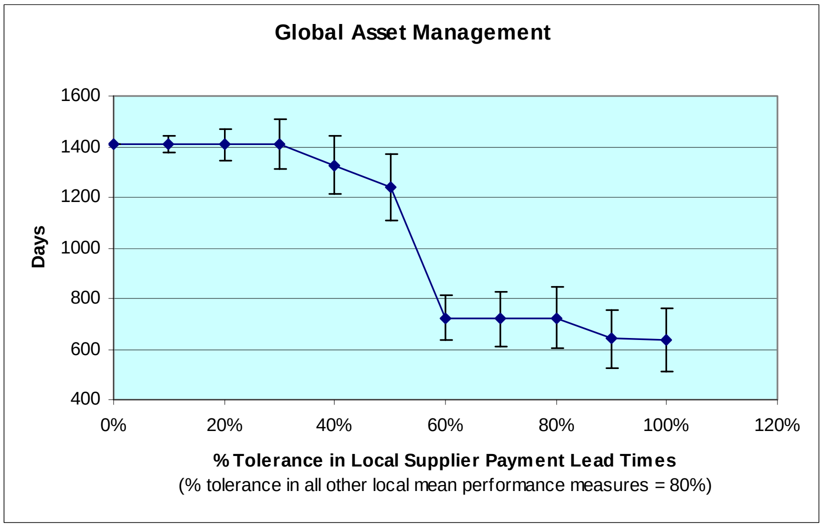


Figure 5.28. Behavior of global mean asset management when other tolerances = 80%.

Experiment 26:

1. Perform 1,000 runs every 10% increase in tolerance of all local mean performance measures.
2. Plot the resulting global mean assets at every 10% increase in tolerance.

The resulting values are shown in Figure 5.29.

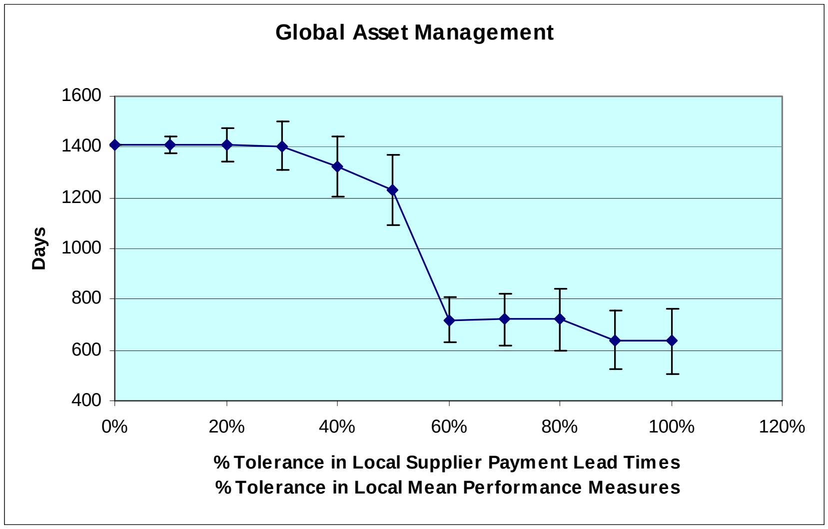


Figure 5.29. Behavior of global mean asset management when all tolerances increment by 10%.

5.6. Discussion of Results

As seen from Figure 5.5 through Figure 5.9, when the percent tolerance in local responsiveness increase, global responsiveness show a slight gradual decrease, *i.e.,* the order fulfillment cycle time will gradually increase. Moreover, the variability in the global mean responsiveness will gradually increase by larger values.

Similarly, as seen from Figure 5.10 through Figure 5.14, when the percent tolerance in local reliability increase, the global reliability shows a slight gradual decrease. Moreover, the variability in the global mean reliability will gradually increase by large values. It is worth mentioning that global reliability will get small as this is the general case.

Nevertheless, as seen from Figure 5.15 through Figure 5.19, when percent tolerance in local flexibility increases, global flexibility shows a slight gradual decrease.

Moreover, the variability in the global mean flexibility gradually increases by large values.

Figure 5.20 through Figure 5.24 show that, when the percent tolerance in local cost increase, global cost remains almost unchanged. Moreover, the variability in the global mean cost will gradually increase by large values.

Figure 5.25 through Figure 5.29 show that, when percent tolerance in supplier payment lead times increases, global asset management decreases. However, the decreasing trend does not follow a predictable pattern. This is because the asset management in build-to-order supply chains is measured by the proposed business sales and profit opportunity metric discussed in CHAPTER 3, which is dependent of the part supplier's responsiveness and cost. Nevertheless, the variability in the global mean asset management is seen to gradually increase by small values.

CHAPTER 6: RESEARCH SUMMARY AND FUTURE RESEARCH DIRECTIONS

6.1. Introduction

This chapter provides a summary of the research, conclusions and future research directions.

6.2. Research Summary

We define a build-to-order supply chain as supply chain activities that supports the on-demand production of modularized agile products with minimal inventories and forecasts. In Chapter 1, the background of the supply chain and its integration within the value chain is illustrated, where the structure of the general manufacturing supply chain is explained. Also, the emergence of the build-to-order concept is introduced with a historical background of the build-to-order supply chain. A comparison is made between the build-to-forecast supply chain and the build-to-order supply chain regarding several aspects. Moreover, two fruitful areas of investigation are discussed along with the specific opportunities within these areas. These two areas explore: (1) multi-objective optimization of build-to-order supply chains, which is of great interest to research frontier and industry practitioners, and (2) modeling variability within build-to-order supply chains and of variability caused by supply chain entities local performance and their impact on the global performance of build-to-order supply chains.

CHAPTER 2 provides a review of the literature related to the evolution of supply chain research, management and practice and the emergence of the build-to-order supply chain. Several areas of supply chain were addressed, including supply chain types and classification, general build-to-order supply chain network structure, and supply chain modeling in research and in industry. Partial listing of current research in build-to-order supply chain, supply chain variability, supply chain performance measurement and supply chain modeling approached are presented.

Gunasekaran and Ngai (2005) claim that research is needed in the area of BOSC design and control.

In CHAPTER 3, five common and widely-accepted supply chain performance measures are formulated from a global perspective. We propose a new methodology for assessing the performance domain of build-to-order supply chains.

We present a new performance measure called Business Sales and Profit Opportunity (BSPO). This new performance measure is more appropriate to describe the assets managed in the case of BOSCs, which produce agile products with relatively short lifecycles.

In CHAPTER 4, we propose a heuristic to generate near-optimal performance of the deterministic BOSC performance through selection of suppliers, manufacturing resources and delivery couriers that improve the overall global performance given the five performance measures, of which some are nonlinear. We call the heuristic the GSCPH. The heuristic performs multiple horizontal and vertical comparisons at the same time to optimize the global performance of the build-to-order supply chain. The experimental results show that the maximum absolute average deviation obtained in any experiment is less than 4% from optimal, while the relevant maximum variation obtained in any experiment is consistently less than 0.5%.

Since, SCOR model quantifies supply chain entities' based on deterministic performance measures and does not capture the stochastic aspect of build-to-order supply chain entities' performance. In CHAPTER 5, we consider variability of the local performance of supply chain entities. The GSCPH heuristic approach is modified to account for this variability and is named the GSCPH-s. The GSCPH-s identifies the best supply chain configuration based on local mean performance and tolerance, *i.e.*, variation of a given percent. The experiments prove that optimizing the build-to-order supply chain setting based on mean performance measures only, *i.e.*, deterministic modeling, will always result in a configuration that is different from the optimization based on mean and tolerance, *i.e.,* stochastic modeling, for the same performance measure and at the same mean value. Stochastic modeling results in causing at least 25% difference in BOSC configuration at every experiment. None of the 30 experiments run show identical best configurations under both stochastic and deterministic conditions. Furthermore, the experiments show that the global performance will get worse as the percent tolerance in local performance increases, while the variation in the global mean performance increases as the percent tolerance in local performance increases.

6.3. Research Conclusions

Several conclusions can be drawn from this research. First, the proposed GSCPH method is an effective method for deterministic build-to-order supply chain optimization. However, in the real-world, supply chain performance will be stochastic making the GSCPH-s more applicable for BOSC design. Second, the existence of small variability in local performance measures at supply chain entities can result in global performance reduction in build-to-order supply chains. Finally, reduction of local percent tolerances will improve the global performance of the BOSC, and hence, selection of supply chain entities with smaller percent tolerances in performance is essential for global performance improvement in build-to-order supply chains.

6.4. Future Research Directions

The following areas are believed to be fruitful areas for further research. First the correlation between the five global performance measures in build-to-order supply chains should be investigated. Gunasekaran and Ngai (2005) suggest investigating the correlation between performance measures in build-to-order supply chains. Knowing the correlation between performance measures will help researchers and practitioners to better predict the stochastic behavior of the supply chain under varying conditions and performance levels, and better understand the system.

Second, validation of the proposed GSCPH-s heuristic by applying it to an industrial build-to-order supply chain should be performed. Finally, identifying and modeling additional performance measures that would impact the global performance of build-to-order supply chains requires further study.

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