Effective quotation for custom products based on virtual supply chain configuration

Li, Qun

2012

Li, Q. (2012). Effective quotation for custom products based on virtual supply chain configuration. Master's thesis, Nanyang Technological University, Singapore.

<https://hdl.handle.net/10356/48911>

<https://doi.org/10.32657/10356/48911>

Year (2012)

EFFECTIVE QUOTATION FOR CUSTOM PRODUCTS
Based on Virtual Supply Chain Configuration

EFFECTIVE QUOTATION FOR CUSTOM PRODUCTS BASED ON VIRTUAL SUPPLY CHAIN CONFIGURATION

Li Qun

School of Mechanical and Aerospace Engineering

A thesis submitted to

Nanyang Technological University

in partial fulfillment of the requirement for the degree of

Master of Engineering

Year (2012)

ABSTRACT

Customization has become a key strategy for sustainable competitiveness for many Fortune 500 companies. Intensifying competition has been pushing companies to make more varieties of products to meet various customer needs and launch new products continuously with shorter product life cycles. To survive in this kind of rapidly changing market environment, companies strive to produce a large variety of products while managing supply chain efficiently and controlling costs effectively. Many companies in the technology sector, like Dell and HP, are faced with increasing challenges to manage assemble-to-order (ATO), make-to-order (MTO) or engineer-to-order (ETO) supply chains to achieve near mass production efficiency. Within the circumstance of ATO/MTO/ETO supply chain management, an interesting topic of research is how manufacturers can generate quotations accurately and efficiently in response to customer requirements. To secure business from potential customers for custom products, it is very critical for companies to have accurate and fast quotation response generation methods that can help them to meet customer requirements in terms of cost target, delivery schedule, customer location and product specification details.

Moreover, globalization and market competition have driven modern manufacturing enterprises to collaborate with a large number of partners in their supply chain to design, manufacture and ship their products to end customers. Outsourcing enables enterprises to grow beyond national boundaries and to leverage capabilities and resources worldwide. Thus, a complex global ATO/MTO/ETO mass customization supply chain network is formed and integrates a large number of business entities which are inter-related in the process of decision-making,

procurement, fabrication, assembly, logistics and distribution activities associated with various families of products. The large number of varieties involved in supply chain activities and the geographically dispersed suppliers and facilities locations pose a great challenge to managing these supply chain networks. With the advance of information and telecommunication technologies, those geographically dispersed supply chain partners and facilities can be linked together virtually and form a virtual organization or virtual supply chain (VSC). In this research, we expand the traditional VSC concept to include the virtual and generic supply chain framework, which can generate specific supply chain configurations in order to solve the quotation response problem.

This research addresses the quotation response problem for custom products via VSC network structure and configuration. An integrated method is proposed to generate quotations efficiently and accurately for custom products. A domain-based framework is employed to identify and coordinate the critical issues among product, process and virtual supply chain configuration to map the process of quotation response from customer domain to product domain and further down to supply chain domain. VSC configuration entails the instantiation of a generic supply chain network into various specific supply chain variants in accordance with diverse customer requirements. VSC manifests itself through the configuration of supply chain networks, in which a large number of entities and their interdependencies in relation to product platform families, process platforms and logistics networks are synchronized coherently. It emphasizes the conceptualization and formalization of the VSC to enhance the power of variety handling, with respect to supply chains as well as products and processes. By analyzing the tradeoffs among various objectives, a

final supply chain configuration is selected as the one that leads to optimal or near-optimal results in terms of the selected criteria.

To validate the practical feasibility and performance of the quotation response via VSC configuration, a case study of a global motor supply chain is developed based on the domain based structures and class concept. The integrated method is adopted to generate quotation response in a rapid and cost-effective way. The result of a case study based on an electrical motor, including supply chain performance in terms of cost and on-time delivery, has demonstrated the potential application of this integrated quotation response method. Although the configuration of actual global supply chains for custom products encompasses more issues than what presented in the case study, the fundamental ideas of the integrated method has been demonstrated and can be extended for practical decision making.

ACKNOWLEDGEMENTS

I have worked under my supervisors, Dr. Arun Kumar, Dr. Roger Jiao for more than 2 years. Currently I am under Dr. Chen SongLin as a part-time research student. I will be forever grateful to them for giving me a chance to fulfill part of my potential in NTU. I even do not know how to articulate how much I have learnt from them.

They were both very generous in giving their precious time to guide and encourage me and share both their knowledge and personal experience with me. It really made my studying in NTU a great period in my life. I would like to take this opportunity to express my deep gratitude to my great supervisors.

I am grateful for the related company that I have interacted with for getting data, letting me investigate their supply chain design process, and help to make my research relevant to their problems.

Finally yet importantly, this dissertation represents a major achievement for me and my parents, who have never hesitate to give me any kind of support that I need emotionally and materially. Without them, I really cannot accomplish it.

TABLE OF CONTENTS

ABSTRACT	II
ACKNOWLEDGEMENTS	V
TABLE OF CONTENTS	VI
LIST OF FIGURES	IX
LIST OF TABLES	XI
CHAPTER 1 INTRODUCTION	1
1.1 Background	1
1.2 Research Motivations	18
1.3 Research Objectives and Scope	21
1.4 Organization of the Dissertation	25
CHAPTER 2 LITERATURE REVIEW	27
2.1 Product Configuration.....	27
2.1.1 Product Family	28
2.1.2 Product Design Architecture.....	30
2.1.3 Complexity of Supply Chain	31
2.1.4 Three Dimensional Concurrent Engineering	34

2.2 Virtual Supply Chain Configuration.....	37
2.2.1 Virtual Supply Chain	40
2.2.2 Virtual Supply Chain Configuration.....	43
2.3 Available to Promise and Response to RFQ.....	46
2.3.1 Available to Promise.....	47
2.3.2 Response to Request for Quotation (RFQ)	49
2.4 Summary	53
 CHAPTER 3 VIRTUAL SUPPLY CHAIN CONCEPTUALIZATION	56
3.1 Introduction.....	56
3.2 Definition of VSC.....	58
3.3 Custom Product Quotation Model for Response to RFQ	61
3.3.1 Cost of Goods Sold (COGS).....	64
3.3.2 Quotation Process Stages	65
3.4 Challenges in Custom Product VSC Configuration	69
3.5 Key Technical Issues	72
3.6 VSC Reference Model	74
3.7 Summary	80
 CHAPTER 4 VSC FORMALISM AND CONFIGURATION	84
4.1 VSC Formalism	84
4.2 Variety Representation	91
4.3 Configuration Process.....	93
4.4 CASE STUDY	96
4.4.1 Entity Classes for Motor Product, Production and Supply Chain	97
4.4.2 VSC Establishment	99

4.4.3 VSC Configuration and Validation.....	101
4.5 Summary	106
CHAPTER 5 DISCUSSION AND FUTURE RESEARCH	108
5.1 Research Summary	108
5.2 Future Research	110
REFERENCES	112

LIST OF FIGURES

Figure 1.1 Quotation Response Problems	8
Figure 1.2 Quotation Response Examples	10
Figure 1.3 Supply Chain Network Representations	12
Figure 1.4 Basic Supply Chain Activities	13
Figure 1.5 Quotation Response Problem Process	24
Figure 2.1 GPPS Example	44
Figure 2.2 Factory Load Allocation Planning (source: Ng and Jiao, 2004)	48
Figure 2.3 Serial Supply Chain Stages and Options	51
Figure 2.4 Quotation Response Problem & Literature Summary	54
Figure 3.1 Quotation Process Stages	66
Figure 3.2 Domain mapping for supply chain configuration	77
Figure 3.3 Domain Mapping and VSC Network	78
Figure 3.4 Virtual supply chain and supply chain variants	80
Figure 4.1 Entity classes defined for virtual supply chain	87
Figure 4.2 VSC formalism based on domains	89
Figure 4.3 Establishment of Virtual Supply Chain	91
Figure 4.4 VSC Configuration Flow Chart	94
Figure 4.5 Constrain Satisfaction Program (CSP)	95
Figure 4.6 Motor Product Structure	97
Figure 4.7 Product family class and routing classes organized as a GPPS	99
Figure 4.8 Motor virtual supply chain network	100
Figure 4.9 Supply demand network of motor product	103

LIST OF TABLES

Table 4.1 VSC variety handlers	93
Table 4.2 Resource class for motor assembly.....	97
Table 4.3 Supply chain entity classes	98
Table 4.4 Customer RFQ requirements for custom motor	102
Table 4.5 Shipping Modes in Distribution Stage.....	104
Table 4.6 Supply chain configuration.....	105
Table 4.7 Quotation Response Result.....	106

CHAPTER 1 INTRODUCTION

This chapter provides an overview of the background leading to this research. The main research problem is identified as providing quotation response effectively for custom products, which aim to address the challenges of coordinating product, process and supply chain decisions in the global multi-site manufacturing supply chain scenario. Providing quotation response efficiently and accurately is critical for focal company to meet customer requirements and win customer orders. An integrated method is proposed for quotation response.

1.1 Background

Recently, customization and product innovations have emerged as two effective strategies for companies to make quick response and adapt to fast-changing market requirements. Intensified competition broke down the previously large mass markets into smaller niche markets demanding higher levels of product variety, and this has pressed companies to introduce new products in much shorter intervals than before. New products are introduced to market with shorter interval and higher variety to meet niche customer requirements, so that companies can generate profit that is more decent by capturing more profitable niche market. Demand diversity, short product life cycle were two main drives for companies to put customization at the center of their strategy focus. At the same time, in order to improve the company's bottom line, companies had to make the manufacturing process more cost effective and supply chain more efficient. Successful companies adopted efficient product configuration, which taking care of both customization and leveraging common materials. They

recognize each customer requirements as an individual requirement and provide each of them with “tailor-made” products (Tseng and Jiao, 1998), while all of the products are derived from a product family with a generic structure, which share the common modules. Product innovations are to increase the rates of changing product family design by evolving to new product families from old product families with rather short period and shorten the process of new product family design. Those companies that innovate more effectively may surpass companies that do not follow the tide. No matter customization and innovation are mainly supply-pushed (based on new technological possibilities) or demand-led (based on social needs and market requirements), they become the key sustainable competitiveness edges on which companies can finally survive. This trend can be observed for products ranging from sneakers with the customer’s own name imprinted on them, to custom beauty products adapting to different customers’ unique skin condition, to personalized food where, for example, each customer picks the ingredients for his cereal (Fixson, 2005).

Mass customization aiming at satisfying individual customer needs while staying near mass production efficiency (Pine, 1993) has drawn many research interests. Mass customization is the perfect strategy to bridge the gap between cost pressures and customer-specific requirements. It combines customer-specific products and services with the efficiency of mass production. The customer who previously bought a standard product can now satisfy walk away with a tailored solution. Furthermore, mass customization provides the basis for successful customer relationship management (CRM) through direct interaction with each customer. Under the mass customization and global manufacturing environment, the products and services must be provided to the end customers via tailored and more complex supply chain strategies instead of a single simple supply chain strategy.

Similarly, companies that traditionally produced custom-made solutions (or industrial customize products) can still manufacture to requirements but on a larger scale at sub-assembly level, thanks to the powerful new product configuration processes and reusable modular product structures, which learnt from mass customization. Obviously, it cuts costs for those companies manufacturing traditional custom-made solutions whose production scale is in much lesser quantity compared with mass customization companies. The ability to reuse parts and information provides savings in design time, cost estimating, procurement, manufacturing, and inventory, which learnt from strategy of mass customization supply chain configuration.

How to generate quotation efficiently and accurately for a new custom-made solution product for the above companies involved in traditionally custom-made solution business is the topic we would like to study in this thesis. Quotation response generation is to establish a bid price to an end customer (or customers) in order to win a contract or a purchase order. Quotation response generation can also help to assess whether a new product can be manufactured and marketed profitably or not. Quotation generated acts as a guideline for product budget and cost control in new product development process, subsequent manufacturing, servicing and warranty processes in the whole product life cycle. In the process of quotation response generation, decisions need to be made for the selection of the most cost efficient manufacturing process, materials for manufacturing, where to produce the products and whether to buy or make at subassembly level. All those decisions affect the final product cost and process of quotation response generation. On the other hand, quotation response generation process can serve as a quantifying vehicle to assess those decisions.

Quotation response generation is critical in the company's decision-making process because it provides the critical cost information to evaluate whether the decision is wise or not with a quantifying method. The various decision-making processes which need the help of quotation response generation includes:

- Does the company have the competency of cost, schedule and quality to meet customer cost, schedule and quality expectation and participate the bidding to offer a custom product quotation to potential customers
- What is the best custom product design to meet the product functionality, quality and cost targets
- Whether to leverage from current product family or start new design from scratch
- Whether to buy (outsource) or make at subassembly level
- What are the most cost effective methods, processes and materials to be used to manufacture the new custom product
- Where is the best manufacturing location to gain the most advantages for various market, logistics and tax considerations
- What is the best or near best supply chain structure and configurations used to generate quotation which can give the company the most competitive cost, schedule and quality in their custom product bidding offer

This research focuses on the relationship between supply chain configuration and quotation response generation. How quotation response generation affects the decision of supply chain configuration, and how supply chain configuration influences the final cost for quotation response generation.

In the evolving global marketplace, with the emergence of e-Commerce and information network technologies, individual firms no longer compete as independent entities, but rather concentrate on their core competencies in the value chain and outsource the other non-core functions to supply chain partners which are located at lower cost regions and more efficiently fulfill those outsourced functions. This transformed manufacturing firms from a centralized, vertically integrated and single-site structure into a geographically dispersed manufacturing network (DMN) (Ferdows, 1997). The DMN can be represented as a multi-site manufacturing supply chain network, which emphasizes strategic partnerships and cooperative agreements among firms that work together to produce and distribute products. A supply chain is referred to as an integrated system which synchronizes a series of inter-related business processes in requirements to: (i) Acquire raw materials and parts; (ii) Transform these raw materials and parts into finished products; (iii) Distribute and promote these products to either retailers or customers; and (iv) Facilitate information exchange among various business entities (Min and Zhou, 2002). Supply-chain management (SCM) is a method to integrate a focal company's operations and decision making with those of all of its suppliers and customers and their intermediaries to get the best performance of the whole supply chain. Performance of any entity in a supply chain relies on the performance of their partners, their willingness and ability to coordinate activities within the supply chain of requirements fulfillment (Swaminathan, 1996). Thus, the real competition is not company against company, but the whole supply-chain against another supply-chain (Christopher, 1995).

Every supply chain has a set of strategic goals and objectives that the all the companies work together to achieve. Such goals and objectives take different forms at

different levels: visions in different companies, mission statements, business directions, plans and key performance indexes, etc. Companies within a supply chain working collaboratively are subject to a set of common goals, agreement, relevant practices and standards, and established coordinate information and material flow procedures to achieve these common goals. How a supply chain differentiates itself from its competitors' is rely on its unique supply chain configuration, flow and process.

Hence, the supply chain configurations become a strategic and critical asset and intellectual property for the enterprises in order to achieve their product differentiation, innovations and customization. As such, supply chain configuration must be thoroughly studied, properly managed and planned.

To do so, supply chain parties, processes, flows and interactions must be recognized, documented, understood, summarized and analyzed before they can effectively managed and automated. There must be easy-to-use visual tools with a set of common modules, which can grasp the gist of knowledge of supply chain so that the persons who manage the supply chain can model and configure the supply chain effectively.

Furthermore, the model must provide simulation and analysis capabilities so that models can be optimized before final configuration design and implementation activities get under way. Such a supply chain model must be open and standard-based so that it can interoperate with other relevant supply chain modeling, execution and management models.

This research discusses the problem of generation quotation response to meet customer requests and win customer purchase orders for custom products. Custom products have two main categories, consumer custom products and industrial custom

products. Industrial custom product (ICP) is different from custom consumer product (target of mass customization research) in the area that it is not commonly available in consumer market. ICP is custom made for industrial applications, which cater for specific individual customer requirements. It refers to industrial equipment and capital goods, such as custom lift and escalator system.

In custom product quotation response problem, figure 1.1 shows that both customer and supplier side are involved. Quotation response is the engagement with customer's quotation requirements and generation the best or near best result to meet these requirements and secure customer orders finally. It starts from sales or marketing department of focal company (supplier side), which directly interfaces with customer, receiving customer quotation inquiry. Then the inquiry (as the input of requirements acquisition) is passed down to manufacturing and engineering department to process as a requirements fulfillment simulation which come out with product configuration, manufacturing process involved, supply chain configuration decision. Then the information of manufacturing cost, lead-time, and resources needed response and feedback to sales and marketing department for generation quotation response to customer.

This research provides an integrated method to generate quotation based on domain based virtual supply chain configuration. Firstly, based on customer's requests of product specification, product family is searched to allocate whether there is a current available product exists in the product family or not to match with all the customer requests. Or else, partial new customization is needed based on the closest current design and reuse some common modules in the current available products. We call the cases of any new customization design by reusing common modules available as engineer-to-order (ETO). Then, related manufacturing process and involved supply

chain partners are decided. Finally, the best or near best cost and lead-time which can satisfy customer request is decided based on the supply chain configuration of each supply chain entities' capacity, cost and lead time. Due to the multi-site supply chain facilities and complexity of different supply chain combinations, there exist more than one supply chain configurations that can meet the same customer requirements. Therefore, we propose an integrated method to find out supply chain configuration with the best or close to best performance in quotation response problem to win the customer requirements and orders.

In order to address the unique challenges in quotation response generation problem, a comprehensive approach spanning sales, engineering, manufacturing and supply chain management need to be identified, by capturing engineering knowledge and using this to automate key business processes across the enterprise. Moreover, this comprehensive quotation response generation approach should help companies to increase sales and win rates while reducing internal operating expenses and shortening lead times for quotation response generation by responding to customer-specific orders more rapidly, accurately and efficiently.

Figure 1.1 Quotation Response Problems

Although it seems only two parties involve in quotation response problem as illustrate in figure 1.1, i.e. customer side and manufacturer side, actually much more supply chain entities are involves in the quotation response problem if we look into details. Customer posts request of quotation to available qualified manufacturers (or suppliers), and then decide requirements awarding by comparing and selecting best performance supplier based on specification, price, cost, delivery support and track record of quality from different suppliers' quotation response.

Quotation response directly links to requirements acquisition and requirements fulfillment process. Speedy and accuracy in quotation response is critical to win customer requirements. After getting quotation request from customer, manufacturer needs to drill down in details into simulation process of requirements fulfillment. Requirements fulfillment is the function of manufacturing (or engineering) and procurement department, it decides how fast the parts can be manufactured with different cost, quantity and specification. Product configuration, manufacturing process selection, factory capacity and production load planning and supplier qualification and selection are critical factors, which can foster an impact the quotation response specification, price, quantity and lead-time commitment.

Therefore, all the above processes and entities mentioned are involved in the quotation response generation process. Supply chain configuration is to optimize the overall supply chain performance by coordinating product, process and supply chain entities. It is an important strategy to allow manufacturers response customer with best terms and conditions, which will help to win the purchase orders from customer finally.

For example, figure 1.2 shows customer, ABC Company, requests a fan manufacturing company for quotation. Customer ABC company provides the

specification requirements, target cost, quantity, delivery time and deliver to location information.

Figure 1.2 Quotation Response Examples

Based on customer requirements, manufacturer (or supplier) needs to decision the BOM, process and supply chain entities related to the processes of raw material procurement, PCB sub-assembly, motor sub-assembly and fan final assembly. How to configure the supply chain entities to achieve the best or near best performance of the overall supply chain is the main issue to be studied in quotation response problem.

However, the supply chain involves various processes, information, material & financial flows with different parties/enterprises, such as customers, partners and suppliers. It gets even more complex when we consider cross-enterprise supply chain that involves peoples and systems from multiple organizations. The knowledge about these cross-enterprise processes spreads throughout various business managers of

involved organizations. There is no single person or place where one can learn about these supply chain processes and knowledge. Furthermore, supply chain typically is not a simple single layer structure but a multi-layer and multi-dimension nested network. A small network within a single enterprise becomes a part (or a sub-network) of a higher-level network, and that higher-level network itself may be a part of a yet broader network and play a different roll in higher level supply chain network. Hence, there are layers of sub-supply-chain in a total supply chain together with process, information and material flows across different enterprises that make supply chain management a very complex problem.

The very first step in managing supply chain configuration is to capture and articulate the knowledge of main characteristics and processes of a supply chain. Before thinking about optimizing the supply chain, firstly we must document and visualize the supply chain characteristics and processes in some common and understandable format (preferably in some graphical notations) which can help to capture our knowledge about the supply chain.

Figure 1.3 shows the typical structure of a global manufacturing supply chain network. Such a supply chain network is operating in a much more complex way than a simple single supplier, manufacturing, customer supply chain, in terms of the volume and complexity of transactions and information exchanges, multi-layer and multi-parties structures and its dynamic and versatile manufacturing environments. With the green supply chain practice, used products may re-enter the supply chain at any point where residual value is recyclable for environmental concerns of reuse and recycle material.

Figure 1.3 Supply Chain Network Representations

Supply chain management is effectively managing the supply chain activities to maximize customer value and achieve sustainable competitive advantages. It represents a conscious effort by the supply chain firms to develop and run supply chains in the most effective & efficient ways possible. Supply chain activities cover everything from product development, sourcing, production, and logistics, as well as the information systems needed to coordinate these activities.

When investigating in the global manufacturing supply chain network environment, supply chain activities can be divided into three kinds of activities, i.e. strategic activities, tactic activities and operational activities. Figure 1.4 illustrated such activities as planning, sourcing, making, delivery, return management and enabling.

Figure 1.4 Basic Supply Chain Activities

Planning is to plan resources (materials) and locations (stocking locations) identified based on projected demand and service commitment. Detail of planning includes on-going basis demand planning, forecasting, replenishment signals, rebalancing of material.

Sourcing is to manage supplier selection and negotiation processes, fulfillment and delivery performance. It decides the procurement of goods and services to forecast and non-forecasted customer demand and aligns the material sources to meet project and manufacturing demands.

Making is to manufacture the products to fulfill customer requirements or forecast. It includes production line setup, manufacturing process, Bill of Material (BOM), product lifecycle, quality control, engineering changes, part attributes.

Delivering is to manage customer requirements and deliver goods to the customer and manage the financial assignment of costs. It includes inventory and warehouse management, transportation management, asset management, compliance (regulatory), and logistics partner management.

Return management (or reverse logistics) is to manage information, logistics process and recycle or salvage process for the routing, disposition and performance of returned materials.

Enabling is to prepare, maintain and manage information or relationships upon which planning and execution processes rely. It includes information technology and infrastructure management, finance management and so on.

Although the manufacturing process platform mainly focuses on the operation of internal activities and resources of manufacturing firm, outsourcing provides practical solutions beyond the boundary of the focal companies. Because of company's strategy focuses more on core competency, cost advantages of buy versus make and lack of technology, resource or capability, more and more companies decide in favor in outsourcing either design or fabrication or both to lower cost areas. No matter what the reason is, how to manage the global multiple-site manufacturing supply chain and how to manage multiple suppliers dispersed in different locations are becoming critical factors to an enterprise's success. It is essential for a successful supply chain that scattered different partners synchronize and cooperate with each other and work together to design, produce and distribute products.

Global supply chains are more difficult to manage than domestic supply chains. Substantial geographical distance between the global entities not only increase transportation cost, but also complicate decision making process of inventory cost tradeoffs due to increased lead-time in the supply (Wood et al., 2002). Different local cultures, languages, and practices diminish the effectiveness of business processes such as demand forecasting and material planning. Furthermore, global supply chain carry unique risks that might influence its performance, such as, variability and

uncertainty in currency exchange rates, economic and political instability and changes in the regulatory environment (Stratton and Warburton, 2006).

However, the latest information technology and e-business practice provide global multi-site manufacturing supply chain with unprecedented flexibility, agility, speed and cost advantages.

The combination of economic, technology and market forces has compelled companies to examine and reinvent their supply chains. To stay competitive, enlightened companies have strived to achieve greater coordination and collaboration among supply chain partners in an approach called “virtual supply chain (VSC) management” (Umeda and Jones, 1997; Gunasekaran and Ngai, 2004). It integrates a manufacturer’s operations with those of all of its suppliers and customers and their intermediaries based on the support of advanced Information and Communication Technology (ICT).

In supply chain management, ICT refers to a combination for all the technologies which are used to manage and control supply chain related data, activities and information exchange between organization, such as EDI, XML, MRP, ERP, CRM, web-based design, Internet, extranet, intranet, electronic B2B, B2C B2G (business to government) and M (marketplace), etc. New business models of e-Commerce, e-Procurement, e-Auction, e-Marketing, data mining, customer relationship management and newly emerged ICT have enable network of companies to form a electronic supply chain (i.e. virtual supply chain) or *virtual organization* to coordinate supply chain decisions, operation and process.

Virtual supply chain (VSC) utilizes information and knowledge as the substitute for inventory, competes on agility and speed, and views partner/customer collaboration as a competitive strategy asset. The successful operation of virtual

supply chain network partnerships mandates that every member must be able to share information with trading partners and customers in real-time, preferably without manual intervention, whenever possible. Moreover, it involves an alliance of separate firms that can bring together a set of core competencies to take advantage of a market opportunity. The VSC is based on developing a suitable network of collaborating companies depending on various resource requirements. The chain starts from market/customer demands and continues until these demands are fulfilled. (Gunasekaran et al, 2004)

Actually, ICT is a tool to actualize the vision of the VSC, acting as the VSC network backbone that integrates the relationships and operations of several-tier suppliers, business partners and customers to meet the requirements of quality, delivery, cost and timely exchange of information within the supply chain network.

Firms in VSC network gain global information visibility across their extended network of trading partners, which can help them to efficiently plan production, quickly respond to fast-changing business conditions via the open, standard-based and virtually ubiquitous internet.

It is also importance for a company to select proper suppliers to fulfill customer requirements by taking into account of product design, process and logistics decisions. Goffin et al. (2006) have stated that supplier management is one of the key issues of SCM because the cost of raw materials and component parts constitute the main cost of a product and most of the firms have to spend significant amount of their sales revenues on purchasing. In spite of the many research efforts that have been put in supply chain management, research considering the coordinated supply chain configuration, supplier selection, product and process design and multi-site allocation is relatively limited (Blackhurst et al., 2005).

The core task of managing a global multi-site manufacturing supply chain is to configure the supply chain and coordinate supply chain entities to reach optimal or close to optimal performance level from the perspective of the whole supply chain. The critical problems of supply chain configuration emerge in the areas of decision making on supplier selection, inventory control, plant location, production capacity planning, resource allocation and material and information flow within the supply chain network. (Graves and Willems, 2003)

Therefore, a number of difficulties elaborated below relate to configure supply chain for quotation response problem.

- (1) Intrinsic complexity and large scale of the supply chain network
- (2) Diversified customer requirements
- (3) Coordination of different entities on decisions for product, process and logistics
- (4) Intricate tradeoffs between different supply chain goals: for example, cost versus supply chain configuration, manufacturing location versus lead-time

A comprehensive and precise model of the supply chain system is the fundamental tool to generate quotation response by understanding complex supply chain and optimizing its performance and cost. The core of supply chain configuration lies in an appropriate modeling tool that can shed light on both the cost related to different supply chain configurations and the actual operational efficiency of supplier selection, product design, manufacturing process and logistics practice.

This research develops an integrated method for quotation response generation based on *virtual supply chain (VSC) configuration* concept to handle the huge complexity and varieties of SCM. The core concept is to manage various supply chain

variants under a generic umbrella, which yields the most optimized or near best cost and efficiency for the whole supply chain. It emphasizes on the conceptualization and modeling of VSC to enhance the power of variety handling, with respect to supply chains, as well as supplier selection, products design and manufacturing processes. A domain-based reference model is deployed to identify and coordinate the decision factors of product, process and supply chains.

Based on the object-oriented modeling techniques, these decision factors are used to model the VSC. We formulate the problem of generation quotation response as a VSC configuration problem with different variety handlers and states in each domain and entity to cope with the varieties in the process of supply chain management.

1.2 Research Motivations

With the development of advanced technologies, a great number of software and hardware tools are utilized to collaborate through the entire electronic supply chain connection, which leads to the emergence of the VSC. A VSC is defined as a temporary, cooperative network that is formed by independent, autonomous companies to exploit a particular market opportunity, under the support of information and communication technologies (Petersen *et al.*, 2001). However, research in VSC has typically focused on enterprise integration and enabling tools such as information and communication technologies (ICT) to achieve real-time and cost effective ways of information exchange among supply chain partners and virtual integration. (Clarke, 1998; Fitzpatrick and Burke, 2000; Van Hoek, 2001; Serve *et al.*, 2002).

These studies exclusively employ an information & communication technology perspective of VSC from the point of view enabling technology and information

system integration. Although such an information system focused perspective provides enterprises with a convenient and real time access to digitized supply chain management, it fails to address the fundamental questions such as:

- (1) What are the factors related to the supply chain varieties?
- (2) How to model a large number of varieties in a complex supply chain?
- (3) How do the supply chain varieties affect the cost of custom product?

Moreover, due to the inherent complexity in supply chains, it is very difficult to design, configure, and analyze supply chain networks using formal and quantitative approaches. Answers to these questions rely on an in-depth understanding of supply chain structure, processes and its configuration. Along this direction, this thesis adopts a generic perspective to describe the complex supply chains and proposes a conceptual VSC configuration methodology to generate quotation response by accommodating the decisions associated with the supply chain varieties.

Based on the ‘generic’ viewpoint, the proposed VSC configuration methodology distinguishes itself from the traditional concept of supply chains on the following two major characteristics. The unique concept for virtual supply chain configuration is it has *a generic structure* and is *cross-disciplined*. Several leading researches have developed some frameworks and models to analyze the supply chain network from various perspectives. However, previous researches are mainly focus on mathematical models or hybrid models to address supply chain configuration and design problems. We argue that these existing models are not easy to be applied to the problem of quotation response generation with complex varieties in supply chains configurations. The challenge in virtual supply chain configuration to solve the quotation response problem is to generate an optimal or near optimal solution, which consists of the products, manufacturing processes and supply chain entities, in requirements to form

an effective and efficient supply chain in a simultaneous and integrated manner. The VSC describes an abstract supply chain network, which is different from real physical supply chain. Thus, we adopt a *generic* structure to represent it and allow this generic structure to propagate into numerous specific complex supply chains with a large number of variants. A generic structure is able to facilitate such a propagation of supply chains with an abstract, concise object-oriented structure. The VSC spans multiple domains, including marketing, product, process, and logistics, which are closely related to each other and contribute to the overall performance of supply chains. Thus, a VSC is expected to account for the inherent diversifications of supply chain variety, as well as the product and process varieties. In fact, by handling the large varieties, we can make supply chain decisions based on the coordinated and integrated decision making process cross the customer domain, product domain, process domain and logistics domain and generate a quotation response finally.

The generic structure of VSC is in line with the generic product and process structure (GPPS) proposed by Jiao *et al.* (2007). While the GPPS is defined in the product and process domains, where specific products and process variants are derived from an integrated framework, the VSC extends the decision framework to the logistics domain, where supply chain variants are generated in the process of supply chain configuration. Moreover, the generic structures defined in multiple domains are interrelated such that decisions in the supply domain must reflect the requirements from the other domains.

The number of possible configurations for a supply chain network is extremely large due to the huge varieties related to supply chains, including product structures, process operations, supply chain network structures, supplier selection and logistics distribution channels. Multiple levels of globally dispersed suppliers exist in a supply

chain network, where suppliers at the lower level provide materials to those consumers at the next higher level and so on throughout the whole network. As each supplier also has its own suppliers and consumers, a supply chain has evolved into a nested network, which can propagate into an incredibly large and complex system. Because of the fact that the companies in a supply chain network may also involve in a number of other supply chain networks and assume different roles, the complexity of the supply chain aggregates.

The purpose of configuring supply chains from a generic structure is to minimize unnecessary changeovers caused by supply chains planned on the ad hoc basis of the traditional way while taking advantages of process, product, design, logistics and supplier selection similarities. In other words, generic VSC structure helps to leverage the similarity and commonality at the maximum level when configuring a new supply chain network from existing supply chain by knowledge accumulating and sharing of supply chain configuration. In addition, this VSC structure provides a common platform for accommodating variety management by unifying various supply data with the associated product and process data into a single entity.

1.3 Research Objectives and Scope

The main objective of this research is to develop an integrated method to generate quotations efficiently and accurately in response to customer's requests for custom products.

This integrated method for quotation response is based on VSC configuration framework, including VSC conceptualization, VSC configuration, and an actual case study by instantiation VSC configuration.

The following areas related to VSC configuration for quotation response problem are identified to accomplish.

Formulation of the VSC, to address issues regarding to VSC concept definitions, VSC functionalities related to the supply chain network with varieties and critical elements handling. The attempt is to provide a basic understanding and overall picture and of VSC paradigm.

Modeling of VSC, after the conceptual understanding is established, the second objective is to model the virtual supply chain for integration and coordination. The fundamental idea is to build a nested system architecture model, which consists of modularized building blocks of elements and processes of VSC under a generic conceptual structure umbrella.

VSC configuration, to address issues of dynamic configuration of the generic VSC network is the third objective of this research. By deciding the status of variety handlers, specific solution of the supply chain design is created. The generic modeling instantiation captures the synergy between various supply chain solutions.

The quotation response problem we studied is restricted by the following characteristics:

- Industrial custom products
- A known product and process structure
- Assembly-to-order (ATO) and Engineering-to-Order (ETO) supply chain
- Global multi-site manufacturing facilities

The reason we consider ATO/ETO industrial custom products is that they represents the major challenges involved in quotation response problems. The results could be extended to custom consumer product and build-to-requirements products by eliminate some constrains in future.

More specific research scopes have been determined in requirements to fulfill each identified research objective.

1) Domain-based reference model:

- The fundamental concepts underlying a VSC are defined, which include objectives, strategies, workflow, constraints and different domains.
- Identify the related domains' reference model of VSC, involving customer, product, process and logistics. Identify the relationship and interactions between domains.
- Conceptualize and analysis the VSC using the object-oriented modeling techniques and class theory.

2) Propose a generic VSC modeling approach, including:

- The key elements identified in the previous step are represented as a hierarchical structure of class, which act as the building block of the VSC.
- Establish nested supply chain modeling mechanism; and the infrastructure of the supply chain network is demonstrated as a cascading of these building blocks.
- The VSC structure is specified as a set of variety handlers, indicating the solution space of VSC configuration.

3) VSC configuration and its evaluation, including:

- Define the VSC configuration problem context.
- Design configuration models for static generic network and dynamic specific solutions.
- Owing to the class-member relationship between SC entities and their variants, specific solutions to the supply chain design is created in the instantiation process.
- Specify the states of variety handlers and the evaluation of candidate solutions against multiple criteria by illustrating on practical case studies.

To help companies improve customer satisfaction, by providing accurate quotation efficiently with detailed BOM, drawings and other technical information to meet custom product specification requirements in RFQ when submit quotation, the proposed virtual supply chain configuration methods can give the end customers more confidence in the overall quotation deliverables. Because the product configuration and supply chain configuration process are taken care effectively with the methods of virtual supply chain configuration, a simplified process of quotation response problem is elaborated below in Fig 1.5.

Figure 1.5 Quotation Response Problem Process

1.4 Organization of the Dissertation

To give a brief idea of the structure of this thesis, we elaborate the organization of each chapter structure and topics as following.

Chapter 1 discusses the general background of quotation response problem. We discuss about SCM and VSC configuration with their considerations. It states the motivation, objectives and scopes of this research as well.

Chapter 2 provides a comprehensive literature review of the state-of-art research in the quotation response problem related areas. The literature is arranged to cover various topics from product configuration, virtual supply chain configuration, 3-dimensional concurrent engineering to available-to-promise (ATP) which are closely linked with specification, quantity, lead-time and cost in quotation response problem.

Chapter 3 introduces the concept of VSC by using a domain-based reference model. Moreover, detail discussions regarding to fundamental issues of the virtual supply chain, in terms of concept observations, characteristics and responding strategies are entailed. A generic formulation of the VSC based on the object-oriented technology is proposed to identify the key elements in relevant domains and their interactions/correlations. This general domain-based structure serves as an umbrella for the further rigorous analysis, simulation, and manipulation of the VSC.

In Chapter 4, the basic supply chain elements and processes, i.e. material inventory, material processing, and material transferring, entail into a set of objects as the building blocks of virtual supply chain models. The whole supply chain is modeled by cascading nested building blocks, which take charge of different supply chain decisions and integrations. A case study of quotation response of a motor company is presented to demonstrate the VSC modeling framework for custom product quotation response.

Chapter 5 summarizes the achievements in addressing the research objectives and tasks. Discussions are given to highlight the contributions. Future possible improvements and research plans of this research work are discussed.

CHAPTER 2 LITERATURE REVIEW

This chapter reviews relevant work addressing supply chain modeling and configuration for custom products. The reviewed literature is grouped into several broad topics, including product configuration, virtual supply chain network and configuration, 3-dimensional concurrent engineering and available-to-promise. In each section, we point out the limitations of the research work to highlight the significance of the research in this dissertation.

2.1 Product Configuration

Due to the localization of market requirements and segmentation of the market for different customer preferences, the outmoded mass market gives way to the rising concept of mass customization. Mass customization requires a synthesis between mass production and the production of highly specialized, individualized products (Pontrandolfo *et al.*, 2002). Tseng and Jiao (1998) pointed out that the essence of mass customization lies in maximizing the congruence of the manufacturer's capabilities with the consideration of customer needs related to target market niches in a timely manner, that is, a manufacturer has to perceive and capture latent market niches and correspondingly develop its technical capabilities to meet diverse customer needs. The mass customization provides advantages and competencies to the companies adopted it, such as, time to market (quick responsiveness), variety (customization), less risk involved (risk management) and economies of scale (mass-manufacturing efficiency).

Mass customization implements an ATO (assembly-to-order) or MTO (make-to-order) production, where firms seek to improve the responsiveness and flexibility of their supply chains through strategic alliance based on their core competencies (Gunasekaran and Ngai, 2005). In MTO production, only the confirmed customer requirements trigger the flow of materials and information in the supply chain (Tian *et al.*, 2002). In terms of the finished goods or component materials, there is very little or no inventory maintained. ATO keeps subassembly module based on forecast and follows by final assembly based on arrival of customer requirements. Thus, requirements lead-time is minimized by this two-stage-value-chain. It helps to minimize risk by designing products with standardized modules as much as possible. With ATO or MTO production, product differentiation is usually postponed to the late stage of product fulfillment, which helps to mitigate the risk and reduce inventory by pooling. (Van Hoek, 2001b) This necessitates various system design considerations, such as product structures, supply chain architectures, and strategic partnership and supplier early involvement (Wemmerlov, 1984; Swaminathan and Tayur, 1999).

2.1.1 Product Family

Many companies are utilizing product families and platform-based product development to increase variety, shorten lead times, and reduce costs. The key to a successful product family is the product platform from which it is derived by adding, removing, or substituting one or more modules to the platform or by scaling the platform in one or more dimensions to target specific market niches (Timothy, 2004). Although there is no standard definition for product family, the common understanding for product family is that product family consists of different flavored yet similar products that share common components, features, designs and subsystems.

Products in the same family have identical main functions, similar product structures, common pool of components, and some specific functions and features (Javier *et al.*, 2000; Galan *et al.*, 2007). Use mobile phone as an example, it needs to have different language keypad and software for different country's local market, and the power adapter for different country is also different due to the different voltage requirement and different form power sockets. Product family allows providing customization and variety for the marketplace without losing commonality between custom products to leverage the effort of design, procurement and manufacturing. Several companies have used product family strategy to successfully design their diverse products such as Sony's Walkman product family (Sanderson and Uzumeri, 1997), Nippon Denso's bicycles (Whitney, 1993), and Swatch watches (Ulrich and Eppinger, 1995). As pointed out by Stadzisz and Henrioud (2005), a product family may have its origin in a differentiation process of a base product or in an aggregation process of distinct products. In the first case, the family represents a product series with different technologies and optional parts and functions due to the product evolution and demand for diversity. In the second case, the family represents the standardization of a series of products whose functions and main components are similar. In both cases, the goal is to form a group of products to reduce their variability and, therefore, to decrease investments and production costs.

Jiao J. et al (1998) present a method of product family configuration by adopting a combination of product family classification tree (PFCT) and a triple-view representation scheme for product family modeling. The triple-view scheme is suitable for modeling various aspects of product families. It captures and conforms to a formal design model, which characterizes product differentiation from a functional viewpoint and describes product families from a technical view in terms of various

design constructs and their interrelationships to describe functional specifications for both product families and their variants.

Timothy (2004) describes basic approaches to product family design. First is a *top-down (proactive platform) approach* wherein a company strategically manages and develops a family of products based on a product platform and its derivatives. The second is a *bottom-up (reactive redesign) approach*, wherein a company redesigns or consolidates a group of distinct products to standardize components to improve economies of scale. Magro and Torasso (2003) describe how product configuration can meet a wide range of customer requirements and increasing control of production by using constraint satisfaction methods to solve a product configuration problem with a number of restrictions. The solution of product configuration must produce the list of selected components (i.e., part lists of both systems and individual components) as well as the product's structure and topology (Sabin and Weigel, 1998). Gupta and Krishnan (1999) investigated the reduction in the complexity of a product family through product design by leveraging common characteristics among the products within the family. Fredriksson (2006) puts forth that a modular assembly process design brings structural disadvantages related to the dispersion of the activities and resource needs.

2.1.2 Product Design Architecture

Along the value chain of product fulfillment, product families are identified as an effective means to achieve product differentiation in accordance with the diversity of customer requirements (Hayes and Wheelwright, 1997; Mayer and Utterback, 1993). Blackhurst *et al.* (2005) propose a model of product chain decision to assist decision-making considering both the operation of a supply chain design and the

effects of product and process design decisions. Fixson (2005) introduces the product architecture perspective to product, process, and supply chain coordination, where the product architecture characteristics, such as modularity, commonality and interface, are analyzed with respect to their impact on different operational strategies. Gupta and Krishnan (2001) propose a mathematical model for costs and benefits of platform-based products, and study the appropriateness of product platforms and their impact on product-planning decision. Kim *et al.* (2002) develop a mathematical model to solve the supply configuration in a single-manufacturer and multi-supplier scenario for a mix of products sharing common raw materials and components. Huang *et al.* (2005) explore the mutual impact between supply chain configuration decisions and product design decisions related to product variety. To tackle the variety issues, process platforms has been developed in the form of standard routings, which facilitate production configuration in accordance with product family design (Jiao *et al.*, 2000). Er and MacCarthy (2006) propose a simulation method to manage product variety in dispersed supply and manufacturing networks. Hence, there is a need to extensive coordination across operations and logistics elements.

2.1.3 Complexity of Supply Chain

In requirements to meet the diversity of customer requirement, companies adopt the strategy of product differentiation, which increase the supply chain complexity exponentially because of a great number of varieties involved. Product configuration reduces the complexity of supply chain by designing products along the product family concept to share the common processes, machines, sub-assemblies and supplier base, but the number of varieties is still huge.

Moreover, the increasing impact of competitive pressures in worldwide market has forced companies to adopt mass customization and dispersed supply chains for product fulfillment. More and more manufacturing enterprises pursue a global manufacturing strategy that aims to transcend national boundaries to leverage capabilities and resources worldwide (Pontrandolfo and Okogbaa, 1999). Companies are changing from supplying domestic market with products, via supplying international market through export, to supply worldwide market with local manufacturing (Rudberg and West, 2006). Additionally, Handfield (1994) mentioned five advantages for companies who choose to source globally—improving quality, meeting schedule requirements, reducing costs, accessing new technologies, and broadening the supply base. These companies may be a single company located globally, or several companies coordinate together to address customers' requirements coherently within extended and virtual enterprises (Bullinger *et al.*, 2000). Fox et al (2000) describe global supply chain as a worldwide network of suppliers, factories, warehouses, distribution centers, and retailers through which raw material is acquired, transformed, and delivered to customers. The characteristics of a supply chain network are distinguished by physical connections, such as number of tiers, nodes and types of participants, and by operations, objectives (Lin and Shaw, 1998). The network structure of a global multi-site manufacturing supply chain provides the manufacturing industries with unprecedented flexibility, agility, speed and cost advantages. Various factors contribute to the cost reduction in a multi-site manufacturing supply chain, such as localization (Lee et al., 1993), delayed differentiation/postponement (Lee and Tang, 1997), etc. Therefore, a global manufacturing supply chain has been recognized as a promising “win-win” strategy for global manufacturing firms.

Outsourcing is the result of globalization supply chain. Much more common than before, both design and fabrication can be outsourced; it is due to either lack of the capabilities or due to the cost. This implies that supply chains play a vital role in the production of complex products made in the world today. They must constantly restructure and simplify their business and fabrication processes and procedures to ensure the profit gaining (Cohen, 1989; Houlihan, 1985)

Such transformation has resulted in an increased use of strategic partnerships and co-operative agreements among firms that work together to produce and distribute products. The success of each firm in such a relationship is now dependent on the actions and results of the other firms (Aissaoui et al, 2007). Thus, various production and operations management decisions of supply chain need to be specified, such as material selection, location selection, inventory planning, load planning, capacity planning, production scheduling, distribution planning.

There is a steady rise in requirements of environmental concerns and government regulations that influence the global supply chain strategies and practices. Hsu et al. (2007) present an analytic network process (ANP) approach to incorporate the issue of hazardous substance management (HSM) into supplier selection. Criteria of HSM competence and a multi-criteria decision model are proposed and then applied ANP to supplier selection, which is characterized by interdependencies among decision structure components.

A complete environmental program for a manufacturing facility is not just about reducing water, energy, and waste, but also maximizing asset utilization through predictive maintenance. Hervani et al. (2005) provides an integrative framework for study, design and evaluation of green supply chain management that integrate works in supply chain management, environmental management, and performance

management into one framework. Chien and Shih (2007) investigate the green supply chain management practices adopted by the electrical and electronic industry in Taiwan, mainly OEM and ODM manufacturers, after the EU implementation of the ROHS and WEEE directives, and conclude that OEM and ODM manufacturers adopted green procurement and green manufacturing practices with advantages of environmental benefit and finance performance. Shawn (2008) discusses the food supply-chain greening effort by hospitals with related environmental-friendly purchasing and waste-management practices. All these considerations and practices increase the complexity of supply chain, and it requires more co-ordinations between supply chain partners.

Integrating business processes is a best practice in supply chain management that involves coordination decisions across multiple facilities and tiers. In practice, firms engaged in Vendor Managed Inventory (VMI) and Collaborative Planning, Forecasting, and Replenishment (CPFR) integrate replenishment planning between companies by sharing sales and promotion information (Sherman, 1998; Lewis, 1999). An integrated, well-coordinated virtual global supply chain is difficult to duplicate and so plays an important role in company's competitive strategies. However, these early models tend to focus on the enabling IT technology aspects. Obviously, more benefits can be derived by simultaneously considering the product, manufacturing process and supply chain aspects.

2.1.4 Three Dimensional Concurrent Engineering

Supply chain is getting more and more complex due to network structure, changes in customer demand, market, competitors and technology. So the

coordination among multiple and often independent companies is a key factor to deliver a product or service to end customer successfully.

The inherent complexities can make modeling of a supply chain a difficult task. Moreover, the complexity is aggregated by the different choices of product family, manufacturing process design and decisions of supply chain design. By reviewing what have done in three-dimensional concurrent engineering (3D CE), we can gain better understand of how to coordinate decisions of product, process and supply chain. 3D CE is mainly studying how to integrate the decisions of product, process and supply chain in new product design stage. Without understanding of these critical decisions made in new product design stage, we tend to lack of better understanding of how to co-ordinate these decisions in product manufacturing stages. Today, much has been written on 3D CE's criticality and benefits. Whereas, we still know quite not enough about how to implement 3D CE to maximize supply chain performance (Forza et al, 2005).

Ho et al (1991) define concurrent engineering as “a system approach to the integrated concurrent design of products and their related processes, including manufacture and support. This concept is further developed into 3-dimensional concurrent engineering by taking into consideration of supply chain design decision-making concurrently. The research cover design for supply chain approach as a strategy of purchasing (Hult and Swan, 2003); the importance of supplier early involvement in the new product design stage (Petersen et al, 2005) and the ongoing trend of outsourcing of both manufacturing and design activities (Caputo and Zirpoli, 2002). By transforming the traditional sequential process of design, production, and delivery/distribution into a parallel one, achieving the so-called “three-dimensional concurrent engineering” (Fine, 2005), supply chain becomes more agile. According to

Fine (1998), three-dimensional concurrent engineering (3D CE) is the simultaneous and coordinated design of products, manufacturing processes and supply chains.

Blackhurst et al (2005) develop a PCDM (Product Chain Decision Model), a high level modeling methodology for describing the operation of a supply chain while considering decisions related to product design and manufacturing process design and the impact of such decisions on the supply chain. PCDM is a high level modeling methodology, which is design to help managers in decision making by using abstracted network to model operation of a supply chain and do quantitative and qualitative analysis. Fixson (2005) propose a multi-dimensional framework, which enables comprehensive product architecture assessment by comparing two alternative product architectures. The framework builds on existing product characteristic concepts such as component commonality, product platforms, and product modularity. Petersen et al (2005) argue that integrating suppliers into the new product development process had direct impacts on manufacturing process and supply chain configuration decisions. Early supplier involvement is a key coordinating process in supply chain design, product design and process design.

Fine et al (2005) introduce a decision support model to evaluate the tradeoffs among potential conflict objectives in 3D CE through a weighted goal programming modeling technique and offer a quantitative formulation of three-dimensional concurrent engineering problem. The weighted goal programming technique seeks to minimize deviations from specified aspiration levels of various objectives, such as cost, lead-time, partnership and dependency. The model enables straightforward representation of the interrelations among multiple objectives and analysis of tradeoffs among those that exhibit conflicts. Huang et al (2004) propose and apply an optimization model to understand the impact of platform product, with and without

commonality. Different decision models in 3D CE evaluate and tradeoff different supply chain decisions based on different examples of specific product design. However, 3D CE mainly focus on the decisions made in new product design stage by concurrently considering how different product designs will impact the other concerns and goals in later stage of supply chain operation. In addition, it only evaluates new product design decisions with specific design examples rather than evaluate the supply chain decisions in a wider and more generic product family scope. Virtual supply chain configuration offers a more generic method of product family and process, supply chain variables and decision making with general product family concept.

2.2 Virtual Supply Chain Configuration

In the custom product environment, supply chain management entails the coordination of decisions associated with customer requirements, product development, production process, supplier selection as well as supply chain network. After an initial structure of supply chain is established, supply chain configuration focuses on the deployment of resources and improvement of the initial network structure so as to achieve optimal performance (Chan and Chan, 2004). The major task of managing a global manufacturing supply chain is to configure the supply chain to reach optimized performance. Accordingly, the supply chain configuration problem emerge where decisions are made on supplier selection, inventory control, plant location, production capacity planning, resource allocation, and material & information flow within the supply network. (Graves and Willems, 2003)

Supply chain management spans organizational boundaries and treats the organizations within the value chain, as a unified virtual business entity (Scott and

Westbrook, 1991) Allocating proper production volume to various manufacturing sites is critical to achieve high utilization of their production capacities (Sathi et al, 1992). Among these supply chain components (e.g. parts, manufacturing processes, products, sub-assemblies, vendors in the supply chain, etc.), various relationships exist, representing dependencies between the components. These dependencies are based on factors such as product design and specifications, agreements among business entities, and product fabrication requirements. A collection of components and the relationships between them comprises a supply chain configuration. (Thomas et al.,1997)

One of the major concerns of supply chain configuration is how to deal with the complexities related to supply chain varieties resulting from the numerous potential suppliers, the immense resource allocation schemes, and the extensive information exchange. The essence of the supply chain configuration for custom product lies in a concept of the case class and a product family architecture centered design process model. It generalizes the framework formulation to represent a broader class of architectural cost-minimization problems under quality constraints (Thomas et al, 1996).

Ideally, the supply chain network should dynamically configure with respect to the dictates of the environment (e.g. vendor choice, customer preference, product choice) (Salvador et al., 2004). It is possible to develop formal mathematical programming problems to represent most of these decisions. Typically, the objective functions in these formulations take into account several performance measures such as, cost estimation, lead-time, highest utilization of resources, throughput performance, and due date. This results in a multi-objective optimization problem

with multiple variables. Generally, this will be an NP-complete problem, for which optimal solutions will be hard to find. (Emerson and Piramuthu, 2004)

One of the research areas in this field has focused on the location-allocation problems, i.e., the selection of location of supply chain entities and the assignment of volume to them. Sathi et al. (1992) study the allocation and configuration of manufacturing resources when the requirements of the product quantity changes.

Kim et al. (2002) develop a mathematical model to solve the supply configuration in a single-manufacturer and multi-supplier scenario for a mix of products sharing common raw materials and components. Based on an analysis of the relationship between production schedule and distribution, Jin et al. (2008) advocate integrating the assembly line sequencing and outbound logistics planning to achieve coordinated decisions at the operational level.

Despite these efforts, these research approaches suffer from two main shortfalls. First, the size and complexity of a real supply chain make mathematical models have to deal with an overwhelming number of variables and constraints. Construction of those complex models to reflect real supply chain circumstances can be very difficult and the computational burden can be heavy. Secondly, they focus on a unique perspective of specific situation, there is a lack of generic structures of supply network from which optimal supply chain variant can be derived and apply to every situation. Such a generic structure relies on deep knowledge of supply chain variety structure and effective modeling techniques. Ng and Jiao (2004) shed light on the generic structure of multi-site manufacturing network, which is part of global supply chain. We will discuss this generic product and process structure (GPPS) in more detail in 2.2.2.

2.2.1 Virtual Supply Chain

Information and communication technology (ICT) are considered as the key factors of supply chain modeling, especially in current virtual environment (Wang and Benaroch, 2004). To stay competitive, enlightened companies integrate its operations with all of its suppliers' and customers' via ICT and conceptually achieve greater coordination and collaboration among supply chain partners in an approach called "virtual supply chain (VSC) management" (Gunasekaran and Ngai, 2004). ICT is focus on enabling technologies to realize VSC management concepts, which are used to manage and control supply chain related data, activities and information exchange between organizations. New ICT methods also bring the new business models in the supply chain. Web trading exchange (also called a hub or portal) supplements the point-to-point communication model of telephone, fax, and electronic data interchange with the many-to-many model of the Internet. Passwords enable users to enter a virtual hub to perform buy/sell activity, including catalog procurement, auctions, and reverse auctions. These methods allow trading partners to communicate and collaborate in real time, offering functionality from demand planning to release accounting to logistics (Gunasekaran and Ngai, 2004). ICT is utilized to perform and automate business interactions among supply chain network. These business interactions do not only focus on buying product from suppliers and selling them to customers, but they cover all kinds of collaboration within supply chains, e.g. distribution requirements forecasting information (Gavirneni, 2006). It has given companies even greater tools for tightly orchestrating relationships across the entire supply chain and creating strategic partnerships and operational linkages with a dynamic web of large and small firms spanning all continents (Vickery *et al.*, 2003).

Along this theme, a sizable body of research has been reported, such as ‘e-supply-chain’ (Disney *et al.*, 2004), ‘virtual enterprises’ (Gunasekaran and Ngai, 2004), ‘virtual logistics’ (Clarke, 1998), etc. E-supply-chain is internet or intranet centric ICT enabled supply chain, which can fulfill requirements and assure supply in the physical sphere with real-time supply chain management features and emphasis on efficiency of supply chain realized by ICT. However, virtual supply chain uses the generic and conceptual model to represent large number of varieties in supply chain and the collaborations between ICT enabled virtual organizations (also referred to as agile, outsourced or seamless organizations), which Greis and Kasarda (1997) defined them as ‘legally separate but operationally interdependent companies focused on responding to a market opportunity’. Virtual supply chain creates a network of suppliers, manufacturers and administrative services to collaboratively accomplish specific objectives, such as flexibility and responsiveness (Fitzpatrick and Burke 2000). Virtual supply chain studies interactions and coordination between customers networked trading partners and suppliers.

Virtual supply chain constructs and integrates the e-supply-chain from the view of strategic and integral supply chain involvement, rather than virtual integration in an operational manner and in segments of the supply chain only (Disney *et al.*, 2004). *Virtual enterprises* use the extended form of supply-chain linked by ICT as building blocks. An effective ICT enabled virtual enterprise’s supply-chain will have a number of benefits. It will increase inventory turnover, increase customer service and responsiveness, reduce costs associated in efficient logistics management, increase returns on assets, streamline purchasing procedures, and improve forecast and central planning abilities (Gunasekaran and Ngai, 2004).

Disney et al. (2004) investigated how e-business affects the supply chain dynamics of an enterprise in an attempt to establish e-business enabled supply chain models for quantifying the impact of ICTs. Serve *et al.* (2002) discussed the merits of supply-chain and business-to-business (B2B), and the impacts that they have on each other. They employed the concept of B2B marketplaces as the participating units in a supply-chain process in requirements to enhance the business process. Wang and Benaroch (2004) studied the supply chain coordination in buyer centric B2B electronic market. Al-Mashari and Zairi (2000) developed SAP R/3-based ERP architecture and a conceptual diagram in an effort to create value-oriented supply chains that enable a high level of integration and communication among all supply chain processes.

Gunasekaran (2004) pointed out that B2B space includes the myriad upstream and downstream transactions that enhance channel coordination and customer relationships. New technologies such as Radio Frequency Identification (RFID), Electronic Data Interchange (EDI), mobile agent, accelerate the evolution of supply chain management from the mass production era to the mass customization era. With matured technology and process of B2C and web-based electronic commerce, e-Commerce has now possibly merged as the most compelling enabler for “virtual supply chain” (VSC). It helps to collaborate much speedy, reliable and cost effective supply chain operations.

In today’s high competitive global environment, ICT has enabled new business models. For example, e-business permits companies to have virtual supply chain, which is to fulfill the functions of procurement, requirements execution, customer service, billing, payment, returns, banking and design optimization via ICT. Furthermore, the standardization of internal process by ERP (Enterprise Resource

Planning) system has improved SCM performance by making more collaboration in supply chain operations, in-depth control of globalization service demand and integration of real-time information sharing possible.

However, the above researches focus too much on enabling technology and implementations of virtual supply chain, and lack of the conceptualization of virtual supply chain modeling.

2.2.2 Virtual Supply Chain Configuration

With the ever-changing, ever-expanding global economy, companies must constantly restructure and simplify their business and fabrication processes and procedures to stay competitiveness. This restructuring frequently involves fundamental decisions regarding to those activities, which need collaboration with business partners. In making these decisions, each enterprise must develop a flexible and real time management system to survive in today's competitive market. Successful supply chain management requires a change by adopting ICT to manage integrating activities and key supply chain process (Gunasekaran and Ngai, 2004).

Moreover, the combination of economic, technology and market forces has compelled companies to examine and reinvent not just their processes and procedures but also their supply chains. To stay competitive, enlightened companies have strived to achieve greater coordination and collaboration among supply chain partners in an approach called “virtual supply chain (VSC) management” (Umeda and Jones, 1997; Gunasekaran and Ngai, 2004). Virtually organizations (also referred to as agile, outsourced or seamless organizations) (Gunasekaran and Ngai, 2004) integrated into supply chain network of suppliers, manufacturers and administrative services to

accomplish specific objectives, such as flexibility and responsiveness (Frizpatrick and Burke, 2000).

All the virtually linked yet separate entities in the supply chain, such as, suppliers, original equipment manufacturers, contract manufacturers, forwarders and logistics service providers, are actually act as a synchronized *virtual organization* because of the on time information sharing, coordination and synchronized supply chain decision making and execution.

The generic product and process structure (GPPS) proposed by Jiao *et al.* (2007) is in line with some of the characteristics of virtual supply chain. While the GPPS is defined in the product and process domains, where specific products and process variants are derived from an integrated framework, the VSC extends the decision framework to the logistics domain, where supply chain variants are generated in the process of supply chain configuration.

Figure 2.1 GPPS Example

The above Fig 2.1 shows a GPPS example of the product structure of S1. The S1 product structure is decomposed into hierarchical 4-layer structure with commonly shared modules (highlighted in blue color) and applied class concept to depict the module characteristics and parts assembly process related to individual module.

Commonly shared modules may share among the different finish products or even repeatedly used in the same finish product, which enable sharing of common manufacturing process and materials. In the context of custom product, individual customer requirements would lead to a custom product characterized by specific values of a set of variety parameters (Jiao et al., 2000). A supply chain variant supports the fulfillment of custom products through the configuration of corresponding entities and flow.

There are two important keys to achieving successful virtual supply chain configuration: a thorough understanding of the business processes and quality practices, and the synchronization material flow and information flow across the supply chain (Wood *et al.*, 2002). Virtual supply chain should design to capture, manage and reuse corporate intellectual property to automate engineering processes for best-in-class manufacturers. Virtual supply chain configuration is flexible, scalable, and designed to enhance and extend existing product-lifecycle-management (PLM) and enterprise-resource-planning (ERP) implementations.

Virtual supply chain is not only consists of company internal facilities, but also suppliers' facilities. Therefore, selecting proper suppliers to fulfill a customer requirements at the most cost effective way is importance for a company to make supply chain management decision by taking into account of product design, process and logistics decisions. Goffin et al. (2006) have stated that supplier management is one of the key issues of global VSC because the cost of raw materials and component parts constitute the main cost of a product and most of the firms have to spend significant amount of their sales revenues on purchasing. Supplier selection decisions change the supply chain structure in fundamental ways, in part because they are based on more broadly defined criteria. Suppliers are typically selected based on the buyer's

perception of the supplier's ability to meet quality, quantity, delivery, price and service level needs of the company (Leenders *et al.*, 2002). Ultimately, purchasing managers summarize these factors so that candidate supplier may be ranked for selection by priorities of different criteria. Manufacturers and service providers have to integrate their supply chain strategies with first- and second-tier suppliers to reduce cost and improve quality and delivery timing by setting up strategic partnership (Wisner and Tan, 2000).

Although the different VSC configuration methods mentioned above provide generic overview of the virtual supply chain configuration and operation coordination, they fail to focus on the cost perspective of the supply chain configuration. Thus, we need to explore more on other considerations (for example, available to promise and cost estimation) which are specific to quotation response problem.

2.3 Available to Promise and Response to RFQ

The specific considerations related to quotation response include available-to-promise (ATP) and supply chain cost estimation. There are various versions in the definition of available-to-promise (ATP). We define ATP concept in our research scope as following: a mechanism that provides a response to customer's requirements in terms of quantities and delivery and due-date based on resource availability. It helps to fulfill customer quotation requirement and generate available quantities, delivery lead-time and cost commitment for customer quotation response.

Supply chain cost estimation needs to address the unique challenges of custom product manufacturers with a comprehensive approach spanning sales, engineering and manufacturing. By capturing engineering knowledge and using this to define the cost related to key business processes across the enterprise, supply chain cost

estimation can enable custom product manufacturers have increased sales and design-win rates while reducing internal operating expenses related to cost estimation and shortening the lead time for quotation response generation. The cost estimation solution should integrate seamlessly with existing enterprise-resource-planning (ERP), product-lifecycle-management (PLM) and computer-aided-design (CAD) systems, helping custom product manufacturers respond to customer-specific orders more rapidly, accurately and efficiently.

2.3.1 Available to Promise

ATP uses un-committed inventory and plans available production capacity in master scheduling to support new customer order promises. Both the additional inventory and extra production capacity should not tie with existing purchase order, so that they are available for new order promise. If the company's manufacturing locations are scattered worldwide, then it needs to consider and coordinate ATP globally, and uses different locations' raw material inventory and capacity for ATP. One of the research areas in this field has focused on the location-allocation problems, i.e., the selection of location of supply chain entities and the assignment of volume to them. For example, Geoffrion and Graves (1974) consider the problem of distribution system layout and DC-customer allocation. Sathi et al. (1992) study the allocation and configuration of manufacturing resources when the requirements of the product quantity changes. However, these early models tend to focus on the logistics aspects.

Porter (1986) identifies two important managerial issues in a dispersed manufacturing environment, namely, configuration and coordination. Configuration is concerned with the location and structure, i.e., where activities are carried out and in how many places; while coordination focuses on the connections among different

activities of firms operating globally. Companies that implement Advanced Planning systems (APS) may integrate production decisions across the supply chain by including supplier inventory and capacity constraints into their scheduling function, striving to avert supply problems before they occur (Rohde, 2000).

Ng and Jiao (2004) formulate a multi-site manufacturing supply chain structure that consists of three layers, multiple distribution centers (DCs), final-assembly facilities (FAs), and sub-assembly facilities (SAs). The bottleneck lies in dynamic factory loading allocation problem (FLAP) from FA to SA based on different SAs' capability and capacity that change over time. The FLAP resorts to a domain-based reference model that captures the interdependencies among markets, products, production volumes, and final-production and sub-assembly facilities.

Fig. 2.2 shows a global multi-site manufacturing supply chain location-allocation problem, it is a simplified conceptual structure of the manufacturing sites and distribution network.

Figure 2.2 Factory Load Allocation Planning (source: Ng and Jiao, 2004)

Kern and Guerrero (1990) analyze the activities of accepting customer requirements and promising them with productive capacity to fill the requirements. The problem is presented in the context of the assemble-to-requirements environment, which requires the monitoring of both a final assembly schedule and a master production schedule. The factors involved in effective decision making for demand management including capacity availability, relative costs, and the relative timing of prospective customer requirements. Wezel et al (2006) show that production planning approaches, ERP systems, and advance planning systems can render some flexibility in production planning to cope with restraints of production process characteristics. King et al report a simulation study that compares alternative procedures for determining master production scheduling (MPS) techniques utilizing the super bill and covering set MPS. The performance criterion for the study is the available-to-promise (ATP) lead-time (customer service level).

2.3.2 Response to Request for Quotation (RFQ)

Cost estimation normally involves cost estimation models, which use mathematical algorithms or parametric equations to estimate the costs of a product. The results of the cost estimation models need to fine-tune with actual process cost later and incorporate with the consideration of business plans, budgets, and other financial planning and tracking mechanisms.

There are different cost aspects that need to consider for quotation response generation. For example:

- **Bill of material cost.** Bill of material is a list of the raw materials, sub-assemblies, intermediate assemblies, sub-components, components, parts and the quantities of each needed to manufacture an end product. (Monk,

2007) The bill of materials relates to customer requirements, product design, materials selection and sub-assembly buy versus made decision.

- **Manufacturing cost.** Manufacturing cost is subjected to method and process selected to manufacture the product, and it relates to production process cost, labor cost, production testing cost, set-up cost, yield loss, waste material and indirect material cost.
- **Non-recurring engineering (NRE) cost** refers to the one-time cost of researching, developing, designing, and testing of a new product. It may contain the NRE cost of out-sourcing design to ODM partners.
- **Supply chain cost.** There are two relevant supply chain costs: safety stock cost, pipeline stock cost. Graves and Willems (2003) introduced safety stock and pipeline stock costs model.
- **Transportation and logistics cost** which related to the transportation, storage and distribution of components, sub-assembly and finish products.
- **Indirect cost.** Profit margin and overhead cost is a certain profit margin that a company has to maintain for sustainable growth. In addition, indirect cost needs to cover the marketing, sales administration cost and interest rate finance cost etc.

Cost of goods sold (COGS) equals the total direct cost of the products that are shipped to consumers. Note that all of these costs are influenced by the decisions made at every product lifecycle stage in supply chain.

Alternatively, we understand these costs are related to the different supply chain configurations. For example, a typical serial supply chain of sheet metal house making custom-made chassis as shown in Figure 2.3 below.

Figure 2.3 Serial Supply Chain Stages and Options

Stamping process (stage 2) includes a variety of sheet-metal forming manufacturing processes, such as punching, blanking, embossing, bending, flanging, and coining by using a machine press or stamping press. The manufacturing process could be a single automated progressive operation where every stroke of the press produce the desired form on the sheet metal part, or could occur through a series of stages by using manual process. Figure 2.3 represents a serial supply chain where raw materials are purchased from external suppliers, transformed into finish goods by manufacturing processes, and then sent through logistics transportation process to end customers.

The options available at each stage of the supply chain are shown in the table above. Graves and Willems (2003) point out by just looking at the cost dollar value and lead-time; it is not immediately obvious which option should be selected at each

stage. At the extremist cases, one can create a high-cost, short production lead-time supply chain or a low-cost, long production lead-time supply chain. This research has two goals. One is to provide a generic representation model to describe the supply chain structure and its options. From this generic model, another goal is to come out an approach that determines the trade-off and the optimal (or near optimal) supply chain configuration that minimizes the total supply chain cost and lead-time. For instance, a supply chain comprised of stages with low direct costs and long lead times may have a low cost of goods sold but a high safety stock cost. In order to balance the trade-offs in the supply chain, we need to know the total supply chain cost and lead-time of different supply chain configurations and the criteria to make the selections. The traditional pricing and cost estimation techniques do not work well for complex custom product. We need more efficient cost estimation techniques to tackle the quotation-generation problem for complex custom products.

Dharmajah and Pawan (1997) analyzed the activities particularly associated with responding to RFQs from a customer and eventually get an order from that customer. They depicted a new paradigm for processing RFQs and methodologies for rapid and accurate estimation of manufacturing cost for modified standard products and custom-made products. The development of rapid cost estimation systems is also discussed.

By applying case-based reasoning and parametric cost estimation, Naken (2001) developed a methodology for rapid and accurate estimation of manufacturing cost for mass-customized products. The proposed methodology for cost estimation shows that case-based reasoning is able to produce reasonably accurate estimation of manufacturing cost of built-to-order products in a very short time-frame.

Ben-Arieh and Li (2003) developed a web-based system that link to designers and manufacturers to provide fast and accurate cost estimation and supplier selection. The system provided process-planning capabilities, machining time and cost estimation, and supplier selection. Customer or designer can submit a request for quotation for its product to a central server that links to various manufacturing suppliers. Then, the server selects appropriate suppliers and helps them generate accurate cost estimation. Ben-Arieh and Li (2007) also presented a cost-estimation model that links activity-based costing (ABC) with parametric cost representations of the design and development phases of machined rotational parts. There is an evident trade-off between the details embedded in the parametric representation and the cost-estimation accuracy. The methods that can be used as early as design time with a rough gauge of cost.

Cuzdrdo et al (2009) summarized a review of conventional and knowledge based system for machining price quotation. The knowledge-based expert system software can be used by machining companies to automate the estimations of costs and price. They also covered the principle cost and price estimation methods in creating quotation response.

2.4 Summary

We study what are the state-of-art researches in the areas of product configuration, virtual supply chain configuration, 3-dimensional concurrent engineering and available-to-promise (ATP) and cost estimation. Figure 2.4 entails how these researches are related to the quotation response problem by taking care of different aspects of quotation response problem, i.e. specification, quantity, lead-time and cost requirements. Product configuration includes the product specification

information, product structure, BOM and even the related manufacturing process to assemble the parts into finish goods. Quantity to fulfill customer inquiry can be decided by ATP simulation. Lead-time is affected by ATP, VSC configuration decisions and 3D CE, which study how to coordinate these decisions. The cost of finish goods depends on all the decisions made related to product configuration, ATP, VSC configuration, 3D CE and methods of response to RFQ.

Figure 2.4 Quotation Response Problem & Literature Summary

While the idea of developing virtual supply chain architectures and configuration is appealing, significant effort is required when incorporating the huge numbers of supply chain entities and the intriguing relationships between the different entities' objectives and capability.

The majority of the researches mentioned are mainly focus on enabling technologies with mathematical model and simulation for specific supply chains to optimize cost, goods, inventories and quality performance indicators at local level instead of goals at the entire supply chain level. With some exceptions, a few papers adopt a generic view of supply chain management. Govindu and Chinnam (2007) integrate supply chain operation reference model with generic methodology for multi-

agent system development (Gaia) to model supply chain. Each agent has incomplete information, capabilities, thus a limited viewpoint; there is no global level system control. Francas and Minner (2008) have developed generic network configuration models to investigate capacity planning and network configuration choices in supply chain with product recovery.

Given the above research effort, we argue that literature is sparse in the area of virtual supply chain generic structure; from which optimal supply chain variants can be derived to boost up the whole supply chain performance. And it has more advantages to use virtual supply chain generic structure to help custom product manufacturers respond to customer-specific inquiries and generate quotation with best (or near best) cost and lead-time from the proper supply chain configuration more accurately and efficiently.

CHAPTER 3 VIRTUAL SUPPLY CHAIN CONCEPTUALIZATION

This chapter proposes a reference model of virtual supply chain to capture the synergy of integration and interaction between partners in virtual supply chain network in order to solve the quotation response problem for custom products. Firstly, we discuss the virtual supply chain definition, which is different from traditional ICT based virtual supply chain definition. Then from the virtual supply chain definition and characteristics, we develop a domain based reference model. Technical challenges as well as virtual supply chain decisions for quotation response are studied in the later part of this chapter. This conceptualization approach helps to resolve fundamental issues of the virtual supply chain modeling and providing quotation for highly custom products.

3.1 Introduction

Mass customization has become a common strategy practiced by many Fortune 500 companies. Although supply chain management is used as an effective strategy to enhance company's competency for many years, customization is an area gained more and more attention in supply chain management lately. Quoting for complex and highly custom products traditionally requires a large amount of manual effort from multiple groups, especially procurement, engineering, manufacturing and sales. Difficulties are developed when significant product knowledge is required to create a quotation. The development of the BOMs, product models and drawings for inclusion

in custom product quotation proposals is time consuming and requires valuable engineering resources.

The virtual supply chain reference model and configuration methods, which we are going to introduce here, captures the latest engineering, manufacturing, and business rules and standards and uses this knowledge to ease off the labor-intensive tasks within the quotation process. The result is the ability to consistently produce quotations with more accuracy in less time, and win more business for companies.

The traditional pricing and cost estimation techniques do not work well for complex custom products; we need more efficient cost estimation techniques that integrate in virtual supply chain configuration to tackle the quotation-generation problem for complex custom products. In today's custom product environment, we need to coordinate of decisions associated with customer requirements, product design, manufacturing processes, supplier selection, resource allocation planning as well as green / sustainable supply chain considerations and activities. However, the number of process varieties (e.g., diverse machines, tools, fixtures, setups, and cycle time) increased exponentially due to product differentiation, which may incur huge costs and increase the production lead-time (Wortmann *et al.*, 1997). To tackle the variety issues, process platforms has been developed in the form of standard routings, which facilitate production configuration in accordance with product family design solutions (Jiao *et al.*, 2000).

A major concern of supply chain configuration is how to deal with the complexities related to supply chain varieties resulting from the numerous potential suppliers, the immense resource allocation schemes, and the extensive information exchange.

Answers to these questions rely on an in-depth understanding of supply chain structure, processes and its configuration. Along this direction, we adopt a generic perspective to describe the supply chains and propose a conceptual VSC configuration methodology to accommodate the decisions associated with the supply chain varieties for more efficient and accurate quotation response generation.

3.2 Definition of VSC

The most significant change from traditional supply chain to a modern custom product supply chain lies in the widely spreading varieties along the supply chain. Each component in the supply chain might have tens or hundreds options in terms of products, suppliers, logistic channels, etc. Therefore, custom product transforms the traditional supply chain into the virtual supply chain (VSC) to cope with the huge number of varieties. A VSC aims to fulfill individual customer custom requirements through the cooperation of worldwide suppliers (no matter material supplier or service supplier) under the support of information and communication technologies, which enable large volume and real time supply chain information and knowledge sharing.

The definition of the *custom product VSC* is differentiating itself from the traditional concept of information communication technology ICT-base integrated VSC in the following aspects:

Firstly, the *custom product VSC* is virtual, which indicates it does not refer to a specific and physically existed supply chain, instead a VSC stands for a generic and conceptual supply chain network, which could be used to derive hundreds of or even thousands of specific supply chains. The VSC network generic framework captures a wide-range of knowledge across product, process and supply chain to cope with the huge amount of variety comes from the complexity of the VSC.

Secondly, the custom product VSC consists of entities that virtually linked together by the ICT. Recent developments in ICT make it more effectively to connect suppliers, producers and customers in a seamless integrated network so that enable supply chain entities to form a *virtual organization*, which they synchronize decisions, make joint planning and scheduling or even design products and manage customers virtually like a single organization. All the virtually linked and yet separate entities in the supply chain, such as, suppliers, original equipment manufacturers, contract manufacturers, forwarders and logistics service providers, are actually act as a synchronized *virtual organization* because of the on coordination and synchronization of supply chain decision-making and execution enabled by information communication technology.

Thirdly, the custom product VSC is described as virtual because it stretches across to many domains/disciplines in the supply chain. It spans from marketing, product, process and logistics four separate disciplines, which have close relationships and impacts between each other. Quotation response problem needs to use different aspects of knowledge from different domain. Therefore, VSC generates a generic and higher level view of the entire supply chain system that includes different domains/disciplines for providing more accurate quotation response.

The VSC distinguishes itself from the traditional concept of a supply chain through its typical features such as high-level virtual and holistic view, high variety, and cross-discipline.

Based on the ‘generic’ viewpoint, the proposed VSC configuration methodology further differentiates itself from the original concept of ICT-base integrated VSC supply chains from the following two major characteristics.

(1) *A generic structure*, several leading researchers have developed some frameworks and models to analyze the virtual supply chain network from various perspectives. For example, Thomas et al. (1997) proposed an object-oriented and knowledge-based mechanism to represent supply chain components; Sadeh et al. (2001) adopted agent-based framework with machine learning for automatic dynamic supply chain configuration for continuous supply chain performance improving; Tu and Farhad (2003) developed a hybrid optimization approach to address the problem of supply chain configuration. However, all the mentioned models are either heavily computational burdened or just qualitatively described the problem, which are hard to apply in real complex supply chains scenarios.

Furthermore, a few studies consider the impact of product family, supplier selection and process platform on supply chain configuration. Jiao and Tseng (2004) discussed concurrent enterprising for mass customization and global manufacturing, which aims to align customers, products, processes, and logistics to deliver increasing product variety with reasonable cost. The key challenge in the problem of custom product quotation response is to generate an optimal solution of VSC, which consists of the products, manufacturing processes and supply sources, and to form an effective and efficient supply chain in a simultaneous and integrated manner. A VSC entails an abstract supply chain network, which could propagate into numerous specific supply chains with a large number of variants. The huge number of varieties arises from various perspectives of the VSC. For example, for each part or component in the product we can select a specific supplier from a set of capable and approved suppliers to produce it. Each supplier can take different logistic transportation modes (land transportation, vessel shipment or air shipment) to deliver its materials to the upstream consumers. In turn, each logistic channel can operate in different conditions

in terms of time, route, cost, size and frequencies. A generic structure is able to facilitate such a propagation of supply chains with an abstract and concise object-oriented structure.

(2) *Cross-domains/disciplines*, the VSC spans across multiple domains/disciplines, including, marketing, product, process, and logistics, which are integrate together and contribute to the overall performance of supply chains. Thus, a VSC is expected to account for the inherent diversifications of supply chain variety, as well as the product and process varieties. In essence, the objective of a VSC is to generate custom product quotation by fulfilling customer unique requirements, which indicates the customer requirements on four disciplines, including cost (*market*), functions and specifications (*product*), quantity and quality (*process*), delivery time and route (*logistics*). Therefore, during the configuration process of a VSC, the supply chain designer has to handle the varieties and satisfy the customer requirements from the above four domains.

3.3 Custom Product Quotation Model for Response to RFQ

Traditional pricing and cost estimation techniques do not work well for complex custom products, because of traditional price and cost estimation techniques cannot handle the large scale of varieties inherited in complex custom products efficiently and accurately. With the custom product VSC configuration solution, the true costs of designing, manufacturing and delivering a custom product are factored in when providing quotation. This eliminates cost estimation guesswork and subsequently the need for price padding to safeguard profitability. With accurate cost knowledge yielding from custom product VSC configuration, unprofitable quotes can be avoided and price padding can be avoided to secure the company's bottom line, and resulting

in more business wins from more efficient quotation response with more competitive pricing.

Custom product quotation generally consists of the cost of goods sold (COGS), supply chain cost, logistics cost, general sales and admin expenditures, finance loan interest, tax and profit margin. The process of response to RFQ is as following. Customers usually request for custom product quotation directly to sales or marketing department. After receiving customer RFQ package, the sales and marketing department pass the set of unique customer requirements for custom product stated in the RFQ package to the manufacturing/operation department to get price quotation for cost of goods sold (COGS). Sometimes the price quotation requirement has to flow to R&D department directly if a very new design or partially new design needs to be started from the scratch when there is no suitable product in the current product family to meet the customer requirements for custom product. Alternatively, in the above extreme case, procurement department might involve to make the decision of making or buying either the whole product or sub-assembly of a portion of the product. i.e. whether to buy a product from someone else via outsourcing the design and manufacturing or to design and build it in-house by the company's own R&D and manufacturing force. It depends on in whichever case the overall cost is lower and whether the final decision can meet delivery schedule to customer location, target cost and product specification requirements or not.

Different cost aspects need to consider for quotation response generation. We divide those cost aspects into 3 major portions. The final price for quotation response does involve cost of goods sold (COGS), transportation and logistics cost and the overhead cost.

Therefore, the model of price quotation for a custom product can be expressed as:

$$Q = C + L + O$$

Where Q is the total price in a custom product quotation; C denotes the cost of goods sold (COGS); L stands for logistics and transportation cost; O represents the overall overhead cost or expenditure.

Based on the cost analysis, previous experience and industry profit margin guideline, the cost of goods sold (COGS) of custom product normally account for over 50% of total price in final quotation. Moreover, the rest compositions of final price can work out from COGS as a percentile based on experience or from known cost models. Thus, investigating the exact price of COGS is critical in overall response to RFQ, because COGS is a fundamental building block of total cost in RFQ response generation.

Cost of goods sold (COGS) consists of bill of material cost, procurement admin cost, in-bound logistics cost, manufacturing cost, non-recurring engineering cost and supply chain buffer cost.

Logistics and transportation cost is related to the transportation, storage and distribution of raw materials, components, sub-assembly in manufacturing stage and finish products in distribution stage.

Overhead cost mainly denotes a certain profit margin that a company has to maintain for sustainable growth. In addition, overhead cost needs to cover the marketing, sales administration cost and interest rate finance cost etc.

Note that all of the cost portions are influenced by the decisions made at every product lifecycle stage in supply chain. There are three major product lifecycle stages

to consider, i.e. purchasing raw materials, manufacturing and transportation cum distribution.

3.3.1 Cost of Goods Sold (COGS)

Cost of goods sold (COGS) equals the total cost incurred in the custom product manufacturing process and the manufacturing facilities before ship the finish custom product to end consumers. It is the major trunk of overall price in RFQ response (over 50% of total price) and it mainly comes from purchasing and manufacturing stages. This session will discuss its cost components in more details.

Cost of goods sold (COGS) consists of bill of material cost, procurement admin cost, in-bound logistics cost, manufacturing cost, non-recurring engineering cost and supply chain buffer cost. Therefore, the model of COGS in price quotation for a custom product can be expressed as:

$$C = C_{BOM} + C_{ad\ min} + C_{in-bound} + C_{maf} + C_{NRE} + C_{buffer}$$

Where C denotes the total price of Cost of goods sold (COGS); C_{BOM} is the bill of material cost which account for all the raw materials used to produce the custom product; $C_{ad\ min}$ stands for the procurement admin cost when acquiring the raw materials; $C_{in-bound}$ represents for the in-bound logistics cost which incurred when bring in those raw material from different locations to the final manufacturing location; C_{maf} entails the manufacturing cost to produce the custom parts; C_{NRE} delegates the non-recurring engineering cost and C_{buffer} is supply chain buffer cost.

The detail elaboration of those cost components is as following. Bill of material (BOM) is a list of the raw materials, sub-assemblies, intermediate assemblies, sub-components, components, parts and the quantities of each item needed to manufacture

an end product (or indicates as the per information of the BOM). The bill of materials relates to customer requirements, product design, materials selection and sub-assembly buy versus made decision. Manufacturing cost relates to method and process selected to manufacture the product, and it incorporates to production process cost, labor cost, product-quality checking cost, set-up cost, yield loss, material waste and indirect material cost. Non-recurring engineering (NRE) cost refers to the one-time cost of researching, developing, designing, and testing of a new product. It may contain the NRE cost of out-sourcing the design (or partial design) to original design manufacturer (ODM) partners. Besides, there are two relevant supply chain buffer cost, safety raw material buffer stock cost and pipeline stock cost.

3.3.2 Quotation Process Stages

The determination of final price for quotation response is weaved into different activities of different RFQ process stages showed in Fig 3.1 below.

Although individual process stage has its own focus, involves different parties and incurs different activities, the whole process needs to have seamless information flow back and forth between stages in order to generate quotation response in a timely manner.

Different input information feed into each stage and different output information flow out from one stage to the next stage as the next stage's input information. Different personnel from different supply chain entities are involved in each stage for information gathering, taking actions, decision making and cost estimation.

Figure 3.1 Quotation Process Stages

We divide the quotation process into four major stages. The first stage is the customer RFQ package stage, which involves customer's procurement department persons and supplier's sales persons to communicate and clarify the customer requirement details for custom product. For example, product specification, target cost, delivery schedule to customer location and required quantity. Sometimes, the product specification is not clearly defined by customer, thus it is very hard to get an accurate cost (or) price for quotation response. It is the duty of supplier's sales persons to work with internal stock holders and clarify/quantify the details specification requirements with customer back and forth many times in order to get it right for the correct and accurate price/cost information in quotation response.

The second stage is the product family matching and design stage, which involves supplier's R&D department, manufacturing operation department and

procurement department to make the decision of custom part design, BOM and manufacturing process based on customer RFQ package details in the first stage.

The third stage is the manufacturing stage whereby the procurement department will acquire the raw materials based on raw materials' lead-time and then the manufacturing operation department will decide the manufacturing plant location and produce the custom part by following predesigned manufacturing procedure and work instructions. The cost of acquiring BOM materials and lead-time of those raw materials, and the manufacturing process cost and lead-time will affect the overall price for quotation response. Thus, clearly define the BOM and production process in the previous stage is critical for accurate cost and lead-time estimation in the third stage. The outsourcing partial design and buy sub-assembly decision needs to be made in second stage, and the decision will impact the total price also.

The final stage is the logistics and transportation stage, which involves third party logistics service providers (3PLs) and distributor channels to deliver the finished custom product to end customer appointed location before required docking date.

Therefore, the air or sea, expediting or normal transportation modes need to be decided based on customer required delivery schedule. Different shipping mode will incur different cost, which will change the total price in final quotation response too.

To summarize, the decisions made in above stages are related closely to the final quotation price of custom product's two major cost components, COGS and logistics cost. Overhead cost, another cost component of final quotation price, usually calculates as a percentile of the sum of COGS and logistics cost. Thus, the formula of quotation price can be transformed into the following representation:

$$\begin{aligned} Q &= C + L + O \\ &= C + L + f(C, L) \end{aligned}$$

Once receiving of customers' inquiries or request for quotation (RFQ), customer and supplier sales department collaboratively work together in order to make customer requirements as clear and as quantified as possible. Then supplier side different departments work closely in attempting to achieve customer satisfaction in the respects of cost, delivery time and correct product, which can fully meet or exceed customer's expectations.

The four process stages incorporate the activities that the communication among people is to articulate the particular customer's custom product needs, to define the corresponding custom product specifications and to estimate the possible cost and delivery time to customer location for responding to RFQ. Various participants from different departments in the same company and different companies along the supply chain are involved. They mainly include customers, salespersons, R&D engineers, procurement, manufacturing operation, logistics and distributor channel partners.

Because of the improper communication, misunderstanding and the limited knowledge owned by the participants, the traditional (non-systematic) quotation response process is often long (perhaps ranging from weeks even to months) and final custom part price estimation is not accurate for quotation response. VSC configuration is a more systematic, accurate and efficient method for custom part quotation response. Although VSC configuration method was developed by Roger et. al. previously mainly for production planning and order fulfillment purpose, it is very promising to extend the application scope of VSC configuration into custom part quotation response arena.

The four quotation process stages can fit into four domains of VSC configuration conceptual model and framework of VSC configuration perfectly as illustrated in section 3.6 Fig 3.2. However, the VSC configuration method proposed

by Roger et. al. does not focus on the cost and price aspects, we need to add in the cost estimation function in this model in order to extend the application boundary of this model into quotation response area. We will discuss in more details in chapter 4, which shows that modified VSC configuration method can provide an effective way to handle to huge varieties in product configuration and supply chain configuration, and render significant help to get accurate price for each cost component in a swift manner and improve the overall efficiency of response to RFQ process.

3.4 Challenges in Custom Product VSC Configuration

Custom product VSC configuration has many unique challenges. These challenges are incurred because of the characteristics of custom product.

(1) Complexity of a supply chain network. A supply chain network is inherently complex due to its multi-level, nested structure. Firstly, multiple levels of suppliers exist in a supply chain network, where suppliers at a lower level provide materials and service to those enterprises at next higher level. Piramuthu (2005) states that the total possible configurations from a supply chain network would be the product of the number of levels and the number of combinations of each level.

Secondly, each supplier has its own suppliers and consumers thus supply chain entities constitute a nested supply chain network. Due to the supply chain complexity, it is also difficult to select suitable and capable suppliers to meet requirements of technology, quality, cost and delivery support.

(2) Diversity in customer requirements. The industry today is trying to meet the diversified customer requirements in requirements to capture bigger market share and gain more profit. It demands for a high variety of custom products, reduced batch sizes and shortened product life cycle as compared with mass consumer products.

Hence, the variations in customer requirements lead to varieties in product design, specifications and manufacturing processes.

To obtain the most profit from the maximum customer satisfaction and fastest services, supply chains need to configure differently for different sets of customer requirements. Frequently, companies are in a situation of struggling to select the most suitable materials, processes and suppliers to meet various customer requirements at the same time. The dispersed locations of materials and suppliers bring about the complexity in logistics decisions such as transport routes planning, transport methods selection, logistics freight costs optimization with the trade off of the transportation time. Multiple transportation legs involved in the delivery of goods from supplier to its customer complicate the logistics decision making.

(3) Coordination of product, process and logistics decision. Custom product and product innovation pursuit for different product design to meet different customer's flavor or evolving of the market needs. Various combinations of different components consist of bill of material (BOM) for each individual design. Different BOM may necessitate a different set or the same set of suppliers. The supplier selection, logistics process and product design decision making in the corresponding supply chains eventually leads to varying impacts on overall system performance. Proper coordination of supply chain decisions with the design and manufacturing process of the products achieve the substantial benefits in that supply chain.

The different logistics decisions influence the performance of each individual company with respect to costs and delivery times from the lowest level of raw material suppliers to the highest level of finish product providers. Consequently, logistics decision making has a major impact on the overall performance of the entire supply chain to fulfill a customer requirements.

(4) *Green supply chain considerations.* Customer who choose custom product normally is environmental conscious and has environmental requirements on custom product too. Thus, it impose challenges on supply chain, such as supplier selection, carbon footprint, environment policy and process, waste management, recycle and reuse, etc. Moreover, it becomes even more challenging to consider these aspects while minimize the total supply chain cost when making supply chain decisions. Green supply chain starts from raw material suppliers to end customers and up to recycling & returning of used products. It pursuits the maximum value in the whole supply chain by addressing the considerations of social and environmental benefits.

(5) *Product design determines the manufacturing process and supply chain decisions.* Design for manufacturing (DfM), design for assembly (DfA) and design for environment (DfE) are getting more and more popular in the industry. Product design changes may affect decisions regarding manufacturing process, testing method, and quality control and product recycle and reuse process. Therefore, the differences in product design and components selection add to the complexity in manufacturing process decision making, such as changes of machine, tools and fixtures set ups, operations precedence, working instructions. Such differences implicate a major influence on the production costs, delivery times and product quality. Hence, product design and manufacturing process is of the similar importance in configuring supply chains. Blackhurst et al. (2005) recognized that there are considerable benefits in configuring supply chains taking into account both the design of a product and the design of its manufacturing process.

Custom product virtual supply chain is very complex to model due to the multi-site supply chain network structure, diverse product families & manufacturing process, different customer requirements. Moreover, recent green supply chain movement

drives for recycle, reuse, *reverse logistics* and *reverse manufacturing* activities in the supply chain, which result in reverse direction material flow and new manufacturing needs and processes.

Nevertheless, the common components, basic structures and similar assembly processes embedded in the product and process variety inherently contain similarity and thus reusability in the corresponding supply chain networks. Therefore, taking the advantage of the repetitions is a key issue in the VSC configure. Leveraging the product family commonality to deliver varieties and reusing proven elements and knowledge of supply chain's activities can also help to reduce mistakes in supply chain decisions.

3.5 Key Technical Issues

As we mentioned above, the custom product VSC is inherently complex due to multi-layer and multi-site (nested and dispersed) supply chain network structure, numerous decision factors associated with the product, processes, supplier selection and supply chain network to optimize its performance. Moreover, there are many uncertain or random events happened in the supply chain every day, for example, customer demand variations, delivery time re-scheduling, production capacity fluctuations.

Therefore, we need a systematic framework and rigorous formulation of the VSC in terms of concepts and functionalities. The framework and formulation lead to a clear understanding of the VSC without any misconception and misinterpretation. It addresses the problem nature of the VSC and paves the way for further investigation of methodologies and solutions. To satisfy the formulation requirement and meet the

technical challenge, the domain-based design theory and object-oriented concept are adopted in this research to build the framework.

In particular, how to handle the high variety and uncertainty of supply chains and how to coordinate supply chain configuration dynamically with product and process varieties are the major challenges in VSC of custom product quotation response problem. In this regards, the following key technical issues are identified for VSC and its configuration.

VSC conceptualization. As different from the traditional ICT-based rational of the VSC configuration, this research proposed a VSC formalization that emphasizes the fundamental understanding of the generic characteristics of a supply chain and captures the similarities among various virtual supply chain configurations. To do so, the problem boundaries have to be clarified and defined. In particular, the key elements (decision variables) that constitute a VSC have to be identified and quantified in requirements to account for information and material exchanged among multiple domains. Furthermore, the infrastructure of supply chain network must establish to facilitate supply chain variety representation.

VSC modeling. The VSC entails a conceptual model that encompasses the overall different companies and organizations to produce a family of products. It must provide a generic umbrella to capture and utilize commonality, under which each new product is instantiated and extended to anchor material production and transportation to a common supply chain structure (Blackhurst *et al.*, 2005). Within the VSC structure, proper suppliers and components are selected and arranged to form an optimal and permissive supply chain for every individual product in the product family.

Variety handling in VSC. Once the VSC being constructed, another important issue emerges, i.e., how to transform the generic structure into a specific solution and optimize it to meet the individual customer requirements. Decisions regarding the configuration of a VSC must accommodate the multiple criteria/objects that might conflict with each other and subject by various constraints across multiple domains.

3.6 VSC Reference Model

A critical step in the research of a custom product VSC is to develop a reference framework that can capture the synergy of inter-function and inter-organization within the VSC network with the consideration of solution propagation of the product families and process platforms. Such a reference framework is critical to understand the operations of a VSC and the impacts of product and process decisions on the structure changes of supply chains.

The VSC entails a conceptual structure and overall logical organizations of producing a family of products. It provides a generic umbrella to capture and utilize commonality, within which each new product fulfillment is instantiated and extended to anchor material production and transportation to a common supply chain structure (Martinez *et al.*, 2000). Within the VSC, proper supply elements are selected and arranged to form an optimal supply chain for each individual product in the family. Decisions regarding the configuration of a VSC are deemed very complicated.

The VSC is inherently complex due to its high variety in the product, process and supply. Product differentiation inevitably leads to an exponentially increased number of process variations, involving machines, tools, fixtures, setups, cycle times, and labor (Wortmann *et al.*, 1997). The demand of large process variations results in

the proliferation of supply entities, which in turn contribute to more complexity of supply chain networks.

Nonetheless, the common components and basic structures embedded in the product and process variety inherently enable similarity and thus reusability in the corresponding supply chain network (Martinez *et al.*, 2000). Therefore, the key issue in the VSC is to configure product family and supply chain network to take advantage of repetitions. Besides leveraging the cost of delivering variety, exploiting product families around supply chain platforms can reduce development risks by reusing proven elements and knowledge in a supply chain's activities (Sawhney, 1998).

The concept of domains originated from the axiomatic design theory has successfully applied in product design (Suh, 2001). In this research, the domain concept is extended into the VSC field. In a VSC, the input is a customer requirements, which represents customer needs (CNs) in terms of functional specifications and transactional requirements including price, volume, delivery time, etc.

The output is a specific supply chain network, which determines location of network facilities and allocation of resources within the network. The VSC spans four domains including customer, product, process and logistics. Complexity arises when these domains interact with each other, leading to conflicting or incompatible solutions. Therefore, this research attempts to streamline the intra-domain, inter-domain relationships within a VSC, and provide decision support to product, process and supply chain design. With this strategy, the specific characteristics of the domains are identified and the semantics of the network relationships are established.

The content of the VSC domains and the interactions between them are illustrated in figure 3.2. Requirements in the customer domain are described as a set

of CNs, which specifies the product characteristics and the transactional terms (e.g., price, volume, delivery time, etc.). In the product domain, product families designed to satisfy the CNs.

A generic product structure is tailored into various specific products, which are organized as bill-of-materials (BOM) of the specific product structure. The process domain hosts decisions on how to decompose the entire production into a series of process operations, which are implemented by the internal assemblies or the external suppliers. Finally, the logistics domain is characterized by the relationship of entities in supply chain network.

For each type of material requirements of product specification, target cost, quality and delivery schedule to customer location passing down from the upstream domains, the downstream domains must select a set of suitable entities to provide the specified material, manufacturing service to meet up stream's requirements. A supply chain configuration is established when the material requirements and the product delivery are allocated to the respective suppliers, assembly plants, and the distribution channels.

Figure 3.2 below shows how the four quotation process stages can fit into four domains of VSC configuration conceptual model and framework of VSC configuration perfectly by mapping the four quotation process stages into four domains of virtual supply chain configuration.

Figure 3.2 Domain mapping for supply chain configuration

The domain-based framework by Suh (2001) focused on the product family design, in which the input is the customer requirement and the output is the product structure.

In this dissertation, this framework is extended from virtual supply chain configuration field into quotation response problem by integrating the four quotation process stages into four virtual supply chain configuration domains mapping. In VSC configuration for quotation response problem, the input is a set of customer requirements, which represents customer needs in terms of product custom specifications and business requirements including product specification, target price,

volume quantity, delivery time to customer location etc. The output is a specific supply chain network, which determines location of network facility nodes, allocates resources over the infrastructure and the cost related to this specific supply chain configuration and cost involved in supply chain manufacturing processes.

The VSC spans from several domains including marketing, product, process and logistics. Complexity arises when these domains amalgamate and interact, which may cause conflicts and contradiction. Therefore, this research applies the domain-based design theory to streamline the complexity of intra-domain, inter-domain relationships within a VSC. With this strategy, major stages of a complex virtual supply chain are represented as particular domains, in which specific characteristics can be established to interpret the complexity of the network relationships.

Figure 3.3 Domain Mapping and VSC Network

Fig. 3.3 above illustrates the relationship between virtual supply chain network and supply chain configuration. There is a generic network, which covers customer needs, product family, process operation, and logistics, while the virtual configuration process is to generate specific supply chain according to the customer needs.

The generic characteristics of the VSC is in line with those of the generic product and process structure (GPPS) proposed by Jiao *et al.* (2007). While the GPPS is defined in the product and process domains, the VSC extends the decision framework to the logistics domain, where supply chain variants are generated in the process of supply chain configuration.

In figure 3.3, along the horizontal line, the generic structures involved in multiple domains are embodied in the forms of product architectures, process platforms, and VSCs. Meanwhile, specific solutions can be derived from the generic structures through an instantiation process, with considerations of the mapping relationships between the consecutive domains.

Given the VSC for a set of predefined product families and a set of customer requirements, an instantiation process is carried out to derive different sets of supply chain variants.

At this stage, decisions are made for (1) the entities to be included in the supply chain, (2) the volumes of materials allocated to the entities, (3) the logistics and distribution route to customer location, (4) the estimated costs, and (5) the time of delivery.

For example, based on different sets of requirements, two supply chain variants are generated from the VSC as shown in Figure 3.4. Each variant consists of a subset of the supply chain entities, which are assigned a specific volume of materials. Based

on the capacity of the supply entities, the cost of the material and delivery time is determined.

Finally, the performance of the supply chain variants is evaluated against various criteria, such as the total cost, the lead-time, and the quality/service level.

Figure 3.4 Virtual supply chain and supply chain variants

3.7 Summary

The domain-based reference VSC framework captures the interdependencies and linkage among markets, products, processes and logistics of the custom product VSC configuration. Under the generic umbrella of this reference model, all kinds of supply chain activities like design, product family and BOM, manufacturing process, purchasing decision making and distribution channels are incorporated into related domains. Domains are integrated by receiving inputs from upstream domain and

generating outputs to downstream domain. The synchronized decision of custom product supply chain is fulfilled through instantiations mappings between domains.

Generation quotation based on designing custom products' structure, manufacturing process and supply chain to customer specifications is a difficult task if the knowledge base across different domains does not help drive the creation of quotation. The custom product VSC solution offers deep, bi-directional integrations with the actual knowledge in different domains; creating quotation that is more accurate efficiently based on customer requirements and captured rules.

In the past, a constantly evolving set of design rules, process standards, and engineering best practices made it difficult to capture, update and reuse knowledge from different domains in corporate wide level. As a result, the same errors in providing quotation often repeated multiple times. With the custom product VSC solution's help to secure knowledge base across domains, it becomes easy to capture lessons learned and prevent repetitive errors. The custom product VSC solution establishes a closed loop learning system delivering continuous improvement and facilitating reuse of accurate, updated supply chain knowledge.

The domain-based VSC framework entails a conceptual structure and overall organization of custom products. It provides a generic umbrella to capture and utilize commonality, within which each new custom product fulfillment is instantiated and extended in order to anchor the supply chain decisions into a common supply chain framework.

Compared with most mathematic models, domain-based VSC framework has its obvious advantages. Most mathematic models assume that all the information is available non-ambiguously at any time. Those conditions are hard to be satisfied in the real scenario. Either it requires long time to collect relevant data to develop

suitable mathematic models or the mathematical models are too complex and take too long time and too much effort to find efficient solutions.

VSC simplify the size and structure of the supply chain by using restricted numerical representing form. In addition, VSC does not limit itself to a specific scenario like mathematic model. Mathematic model's exclusion of uncertainties (black swan events happen more often than we think in real cases) and its necessity of making strong assumptions make it difficult to accommodate new issues. Whereas, the VSC model adopts a more generic structure which enhance its maintainability and reusability.

VSC conceptual model and framework provide straightforward graph representation and powerful analysis tools to solve the quotation response problem for custom product. VSC's modular architecture ensures that when handling the quotation response problem for custom product per customer requests of product specification, customer location, target cost and delivery schedule, supply chain can be configured quickly by reusing historic solutions and previously learnt knowledge.

The domain-based framework and formulation of VSC lead to a clear understanding of the VSC without any misconception and misinterpretation. It addresses the problem nature of the VSC and paves the way for further investigation of obtaining accurate cost/price information methodologies and solutions in a efficient way for response to RFQ problem.

Based on the understanding of customer requirements in quotation response problem, to satisfy the formulation requirements and meet the technical challenge in VSC modeling, the domain-based design theory and object-oriented concept are adopted in this research to build the framework.

In order to handle large amount of varieties in custom product quotation response problem, we apply a nested modular modeling approach to manage varieties of multiple domains and multiple-tier structure in a VSC configuration way.

A large and complex supply chain network is represented as a series of cascading nested models. The technical challenges in using VSC modeling approach in quotation response problem for custom product lies in the analyzing of typical structure of the virtual supply chain and identifying basic elements and common behaviors.

CHAPTER 4 VSC FORMALISM AND CONFIGURATION

This chapter introduces an integrated VSC formalism methodology for virtual supply chain configuration in order to solve the problem of quotation response for custom product. Moreover, by integrating the quotation response concerns into the VSC formalism, we extend the application boundary of VSC formalism's generic framework. In order to apply the custom product VSC configuration mechanisms within a real supply chain, a case study of configuration a custom-made electrical motor's supply chain is presented for in-depth study of the problem of custom product quotation response. Through this case study, decisions with respect to tradeoffs of various supply chain configurations versus the unique set of quotation response requirements are validated. The linchpin of modeling supply chain configuration lies in the coordination of product, process and logistics decisions in relation to a variety of customer requirements.

4.1 VSC Formalism

The most significant character in supply chain configuration is the widely spreading varieties along the supply chain. Each supply chain might have tens or hundreds options in terms of products, suppliers, logistic channels, etc. Therefore, the virtual supply chain (VSC) method is applied in order to handle the huge number of varieties compared with the traditional concept of information technology enabled virtual supply chain. A VSC configuration method aims to fulfill customer RFQ requirements of custom product through the cooperation and coordination of

worldwide suppliers and logistics partners under the support of information and communication technologies.

The VSC concept mentioned here differentiates itself from the traditional concept of a supply chain through its typical features such as virtual, high variety, and cross-discipline. The VSC is virtual, which indicates it does not refer to a real or physical supply chain. A VSC entails a generic supply chain network, which could derive to hundreds even thousands of specific supply chains. Huge amount of variety lie in every part of the VSC. Each part or component in the product has multiple capable suppliers to produce it. Each party can take different logistic channels to deliver its materials to the upstream partners. Each logistic channel can operate in different conditions in terms of time, route, cost, size and frequency. Moreover, VSC is virtually spans through sales & marketing, process, product and logistics four different domains. The decision made from those four domains affect the price/cost in quotation response to meet customer requirements of custom product in terms of target cost, product specification, customer location, quantity, and delivery schedule. Therefore, when configure a VSC to meet customer quotation requirements, the supply chain designer need to consider how to handle the varieties and satisfy the customer requirements of custom product on all of the four domains.

The VSC configuration aims to address a complex series of problems related to custom product's supply chain configuration in quotation response problem, which are characterized as multi-objective, multi-criterion, multi-function and multi-domain. These necessitate a rigorous formulation of the VSC, including a comprehensive ontology to prevent confusion and misunderstanding.

Definition A.1: An entity is an abstraction of the objects involved in the customer requirements fulfillment process. An entity class (E) includes three sub-

classes, i.e., $E = \langle C, F, S \rangle$, where C , F , S stand for the component class, the operation resource class, and the supply chain entity class, respectively.

Definition A.2: A component class (C) is a set of entities that constitute a product: $C = \langle C^M, C^P, C^S, C^D \rangle$, where C^M , C^P , C^S and C^D defines the classes of raw material, part, sub-assembly, and end-product, respectively. Raw materials are to be transformed into parts or products through the fabrication processes. Parts and sub-assembly are intermediate components that constitute a product. The selection of raw material, parts and sub-assembly for specific finish product is completed in the product design stage (or NPI - new product introduction stage). Via DfE (design for environment), environmental concerns are addressed into green raw material selection, green components/parts selection and sub-assembly design in the product design stage.

Definition A.3: An operation resource class (F) refers to a set of facilities used in the production process: $F = \langle F^W, F^T, F^S \rangle$, where F^W , F^T , and F^S stand for the work center, cycle time, and setup classes, respectively. A work center class refers to the types of machines or workstations that carry out an operation. The cycle time class indicates the processing time of an operation under specific production conditions. The setup class denotes various types of tools, fixtures and setup requirements associated with an operation process. Work center, processing time and setup describe the general characteristics of designed manufacturing process. In green supply chain, green manufacturing process can lead to saving of raw material, energy and pollution reduction. For example, to reduce hazardous materials, we need to select lead-free soldering process for PCB assembly.

Definition A.4: A supply chain entity class (S) is a set of entities that constitute the supply and delivery network: $S = \langle S^S, S^M, S^D \rangle$, where S^S , S^M , and S^D stand for

the supplier, manufacturer, and distributor classes, respectively. The selection and management of correct suppliers, manufacturers (outsourcing partners or own plants) and distributors in supply chain is a critical control link to facilitate supply chain strategy.

Definitions A.1~A.4 describes the elementary classes in multiple domains of a supply chain. A hierarchical structure can be established to represent the relationship among these classes as shown in Figure 4.1. It establishes the foundation for a generic representation of the customer needs, products, processes, and supply chains for custom product RFQ requirements.

Figure 4.1 Entity classes defined for virtual supply chain

Definition B.1: A customer requirements class is defined as a 4-tuple, $O = \langle O^D, O^Q, O^L, O^C, O^T \rangle$, where, $O^D \subset C^D$ represents the specifications of a product, and O^Q, O^L, O^C and O^T refers to the required quantity, the location of the customer, target cost and requested delivery schedule to customer location respectively.

Jiao *et al* (2007) define the customer requirements class mainly applied for production planning and order fulfillment areas, thus their definition of customer class does not include target cost this unique requirement for RFQ quotation response

problem of custom product. In order to expend the application of the methodology of VSC supply chain configuration into quotation response problem for custom product, we especially add in target cost in customer requirements class to denote the cost/price information, which is an essential requirement in RFQ quotation response problem for custom product.

Definition B.2: A *product family class* is defined as a tuple, $P = \langle I, \succ_1 \rangle$, where $I \subset C$ is a class of item, and $\succ_1$ is a class of the precedence relation in a tree-form. A tree-form precedence relation $\succ_1$ is irreflexive and satisfies: $((X, Y) \in \succ_1) \wedge ((X, Z) \in \succ_1) \Rightarrow Y = Z$, where X, Y , and $Z \in I$. Therefore, a product family, $P \subset I \times I$, contains the pairs of items from I that are related by $\succ_1$. It defines a generic bill-of-material (GBOM) structure of the products (Jiao *et al.*, 2000).

Definition B.3: A *routing class* is defined as a tuple, $R = \langle U, \succ_1 \rangle$, where U is the class of operations, and $\succ_1$ is a class of the tree-form precedence relation. An operation class is defined as $U = \langle U^I, U^O, U^F \rangle$, where $U^I \subset C^M \cup C^P \cup C^S$ denotes the classes of input components of an operation, $U^O \subset C^P \cup C^S \cup C^D$ denotes the classes of output components of an operation, and $U^F \subset F$ denotes the resource classes required to carry out the operation. Therefore, the routing $R \subset U \times U$ contains the pairs of operations from U that are related by $\succ_1$. It defines a generic bill-of-operation (GBOO) structure of the production processes (Jiao *et al.*, 2000).

Definition B.4: A *VSC class* (V) is defined as a three-tuple, $V = \langle \Lambda, \Gamma, \succ_2 \rangle$, where $\Lambda \subset S$ is the class of supply chain entities, $\Gamma \subset C$ is the class of material flow between two supply chain entities, and $\succ_2$ is a class of the precedence relation in a net-form. A net-form precedence relation $\succ_2$ is irreflexive. However, as different

from a tree-form precedence relation ($\succ_1$), it allows one preceding node to be connected to multiple succeeding nodes. For example, a supplier may provide components to several different assembly plants. Therefore, the VSC class, $V \subset \Lambda \times \Lambda \times \Gamma$, contains the pairs of supply entities from Λ , where the preceding entity provide material type $\gamma \in \Gamma$ to the succeeding entity.

The customer requirements, product family, routings, and VSC classes are collectively called the *reference classes*. The mapping for quotation response problem into customer requirements fulfillment process involves a series of mapping from the customer domain to the logistics domain as shown in Figure 4.2.

Figure 4.2 VSC formalism based on domains

The customer RFQ requirements class accommodates various types of customer needs, which is mapped into the product domain through the product planning and product configuration process. The product family represents a generic structure of

the product configuration in the form of $\langle I, \gamma_1 \rangle$ tuple. Similarly, process planning facilitates the establishment of the process configuration, which is organized as a generic process structure, i.e., the routing $\langle U, \gamma_1 \rangle$. The product family class and routing class are equivalent to the GPPS, which can be established through the process platform planning (Jiao *et al.*, 2007). In this research, the GPPS is assumed to be an already acquired knowledge base from previous experience and can be transformed into the formulation of product family classes and manufacturing process routing classes.

A VSC consists of the supply chain entities and the allocation of material flows among these entities. It ensures the fulfillment of customer RFQ requirements and generates quotation response for RFQ in a timely and cost-effectively manner. A VSC is derived by mapping the operations in the routing class into corresponding assembly entities, and identifying the suppliers and distributors that are related to each assembly entity. With emphasis on the focal manufacturing entity, we assume that only one layer of supplier and one layer of distributor are involved in the supply chain. This process of constructing VSC can be expended to multiple layers of suppliers and multiple layers of distributors in a more complex supply chain.

The procedure of VSC formalization is shown in Figure 4.3. Whereby all the manufacturing supply chain entities are identified first based on the different functions it performs in a supply chain manufacturing process. Following by the routing class definition, which forms a tree structure, it indicates the relationship of different manufacturing operation processes in order to build the finish custom product. Then different supply entities are matched with respective manufacturing process. With the materials flow from one entity to another entity in the supply chain which performs different manufacturing process in the routing tree structure, the

finish product is completed finally via different virtual supply chain routes and configurations.

1. *Identify all manufacture supply chain entities $\Lambda \in S^M$*
2. *Retrieve the routing class; establish a tree structure of the operations $R = \{u_i \succ_1 u_j\}, \exists u_i, u_j \in U$.*
3. *For all $u_x \in U$, find the set of supply chain entities:
 $\Lambda_x = \{\lambda_{x1}, \lambda_{x2}, \dots, \lambda_{xm}\} \subset \Lambda$ that perform the respective operation.*
4. *For all $u_i, u_j \in U$
 If $u_i \succ_1 u_j$
 Then the precedence relation exist: $\lambda_{ix} \succ_2 \lambda_{jy}, \exists \lambda_{ix} \in \Lambda_i,$
 $\lambda_{jy} \in \Lambda_j$; and the flow of material satisfies:
 $\gamma_{ix-jy} = u_i.output = u_j.input \in \Gamma$.*
5. *For all $\lambda_i \succ_2 \Phi$, where $\lambda_i \in S^M$ // A final assembly entity
 Find $\lambda_j \in S^D$; Establish the relation: $\lambda_i \succ_2 \lambda_j, \gamma_{i-j} \in C^D$.*
6. *For all $\Phi \succ_2 \lambda_i$, where $\lambda_i \in S^M$ // A part fabrication entity
 Find $\lambda_j \in S^S$; Establish the relation: $\lambda_j \succ_2 \lambda_i, \gamma_{j-i} \in C^M$.*

Figure 4.3 Establishment of Virtual Supply Chain

4.2 Variety Representation

The fundamental concept of generic variety configuration originates from object-oriented modeling in a VSC. Every object class defined in a VSC can be considered as a generic item, and every specific element in a supply chain can be considered as an instance of the generic item. The instance of an object encompasses all the properties/parameters of the object and the specific variants' value of those properties belong to that instance only. These generic items are analogous to the classes in object-oriented modeling, and a concept of variety propagation is used for indirect identification of individual variants from generic items. In this research, a

variety handler and its state are defined to represent the VSC and its varieties for every instance of generic class.

Definition C.1: For an entity class $e_x \in E$, a set of variety parameters $P_x \equiv \{p_{x1}, p_{x2}, \dots, p_{xm}\}$ is identified to represent the characteristics of e_x . The variety handler (Θ_x) of entity class e_x is defined as the vector of variety parameters, i.e., $\Theta_x = \bar{P}_x = [p_{x1}, p_{x2}, \dots, p_{xm}]^T$.

Each variety parameter associated with e_x may take one or a few alternative values, known as parameter values, i.e., $p_{xk}^* \equiv \{p_{xk1}^*, p_{xk2}^*, \dots, p_{xkn_k}^*\}$, where p_{xk}^* denotes the value set of variety parameter p_{xk} , and n_k is the number of alternative values.

As a notational convention, the superscript ‘*’ is used within the generic variety representation to denote the variant of a generic item, the instance of an object class, or the value of the variety parameter. Therefore, the variety characteristics of an entity variant $e_x^* \in E_x^*$ are inherited from the generic entity E_x , where E_x^* is the set of entity variants of an entity class.

Definition C.2: The state (Θ_x^*) of an entity class refers to the vector of specific values of the variety handler (Θ_x). i.e., $\Theta_x^* = \bar{P}_x^* = [p_{x1-i_1}^*, p_{x2-i_2}^*, \dots, p_{xm-i_m}^*]^T$, where $p_{xk-i_k}^* \in \{p_{xk1}^*, p_{xk2}^*, \dots, p_{xkn_k}^*\}$ and n_k is the number of alternative values for p_{xk} and i_k is the index of the parameter value. Accordingly, the state of the variety handler can be considered as a particular element in the parameter value space of the entity variants, i.e., $\Theta_x^* = \bar{P}_x^* \in \{\Theta_1^* \times \Theta_2^* \times \dots \times \Theta_m^*\}$.

As an example, the variety handler of the supply chain entity class, Λ , is shown in Table 4.1. A state of Λ can be specified as: $\Theta^* = \Lambda^* = [True, 500, 16, 0.5]$.

Table 4.1 VSC variety handlers

	Variety handler (Θ) of entity Λ	Parameter values
<i>Include</i>	$\Lambda.incl$ indicates whether an entity is included in the SCC or not.	[<i>True</i> , <i>False</i>]
<i>Quantity</i>	$\Lambda.quan$ shows the quantity of components assigned to the entity.	(integer)
<i>Lead time</i>	$\Lambda.time$ is the time between receiving the requirements and delivering the component.	(integer)
<i>Unit cost</i>	$\Lambda.cost$ is the unit cost of the component produced by Λ .	(real number)

The reference classes are built based on the multi-level hierarchical structure of entity classes, which enables inheritance among the reference classes and a hierarchical composition among the instances of the classes. Thus, a class-member relationship is evident between the generic reference models and their variants. Therefore, instances of the reference classes, including customer RFQ requirements, products, routings, and supply chain configuration, can be derived from the generic models of the reference classes. The determination of varieties from the generic models is formulated as a VSC configuration in quotation response problem for custom product as discussed in the next section.

4.3 Configuration Process

In the context of custom product, individual customer requirements in custom product order leads to a custom product characterized by specific values of a set of variety parameters. A supply chain variant supports the fulfillment of custom products through the configuration of corresponding entities and flows.

Figure 4.4 shows the flow chart of VSC configuration process, from initialization, variety handler specification, configuration of supply chain variants to supply chain configuration validation.

Figure 4.4 VSC Configuration Flow Chart

VSC configuration adopts a mechanism of mapping, which involves the following steps.

(1) *Initialization*. A customer requirements (or RFQ) is described as a set of variety parameters and their values: $o_x^* = (o_x^{D*}, o_x^{Q*}, o_x^{L*}, o_x^{C*}, o_x^{T*})$, where $o_x^{D*}, o_x^{Q*}, o_x^{L*}, o_x^{C*}$ and o_x^{T*} stand for the custom product specifications, the actual required quantity of the custom product, the location of the customer, target cost and the expected delivery time to appointed customer location.

(2) *Variety state specification*. Based on planning or configuration rules, the designer constructs a supply variety grid, which lists all feasible variants of each generic item of a VSC, referred to as a variety state. Usually the feasible combinations of variety parameter values are specified by defining, for example, include conditions, planning rules (Jiao *et al.*, 2000), and configuration constraints (Sanderson and Uzumeri, 1997). The specification of the variety state is also known as the instantiation of supply chain entities. Valid variants are identified from the supply

variety grid by matching their variety states with the customer RFQ requirements through constrain satisfaction program (CSP) algorithm as indicated in Figure 4.5.

Given :	
$\alpha_i = (P_i, Q_i)$	
$\{P_i : \text{Product Spec}\} , \{Q_i : \text{Qty}\}$	
Find:	
$V_i = V_{FA} \cup V_{SA} \cup V_{SC}$	
$\{FA_i : \text{Final-assembly Facilities}\},$	
$\{SA_i : \text{Sub-assembly Facilities}\},$	
$\{SC_i : \text{Suppliers and Logistics Providers}\}$	
Satisfy:	
$V_i \in D$	Domain Constraint
$\Gamma^c(FA_i, SA_i, SC_i)$	Capacity constraints
Minimize:	
$c = C(V_i)$	Aggregate cost of V_i
$t = T(V_i)$	Aggregate process time of V_i

Figure 4.5 Constrain Satisfaction Program (CSP)

(3) *Configuration of supply chain variants.* The flows of material among the supply chain entities are determined, and the precedence relationships are finalized. A supply chain variant, $V^* = (\Lambda^*, \Gamma^*, \succ_2^*)$, is developed as a specific network structure.

(4) *Supply chain configuration validation.* The candidate supply chain configurations, i.e., the variety states are evaluated against multiple criteria, such as, confirmation to product specifications, cost, and on-time delivery to customer location. The final supply chain is selected as the one that lead to optimal or near-optimal results in terms of the selected criteria.

It was very difficult to educate sales and design teams about ever-changing manufacturing capabilities or let them understand there are needs to incorporate

design for manufacturing concepts when they make quotation response for customer RFQ. Custom product RFQ VSC configuration allows manufacturing process to influence the quotation response and design of products from the very beginning by considering the manufacturing capacity constraints. The custom product RFQ VSC configuration solution incorporates the rules of manufacturability into the sales and engineering processes upstream, enforcing these often over-looked capabilities and constraints from the outset, resulting in more accurate quotation response for customer RFQ and fulfilling custom order with fewer errors after successful in quotation response and securing customer order finally.

4.4 CASE STUDY

In order to testify the VSC configuration framework's application in RFQ response, we use it in a case of RFQ response for a custom motor. The company produces over 800 types of motors for worldwide customers. Most of the motor products are custom with small batch sizes according to the particular customer requirements. The company employs an ATO/ETO production scheme, where the components of the motor are out-sourced to global suppliers, and the major assembly operations are carried out in several dispersed assembly plants. The finished products are shipped to and distributed through the DC, which is located close to the customers.

When this company receives a customer RFQ requirement for a custom motor, the sales department needs to work with designers to select a suitable custom motor from currently available electrical motor family. The custom electrical motor supposes to manufacture via specific production processes by different entities or resources in a supply chain network with different finish product cost. Finally, the

lowest cost supply chain, which can meet the customer target cost and delivery schedule, will be selected for RFQ response.

4.4.1 Entity Classes for Motor Product, Production and Supply Chain

For illustrative simplicity, the motor structure is reduced to four major sub-assembly manufactured parts, including a base (C_1^P), a rotor (C_2^P), a stator (C_3^P), and a shield (C_4^P). Further, a base and a shield form a case assembly (C_5^S); a rotor and a stator form a drive assembly (C_6^S). The finish product is the motor itself (C_7^D). Figure 4.6 shows how to specify component class structure of the custom motor product from sub-assembly level to finish product level.

The set of resource classes for assembling the motor product is specified in Table 4.2, which involves three types of work centers, cycle time and setups.

Figure 4.6 Motor Product Structure

Table 4.2 Resource class for motor assembly

Work center (F^W)	Cycle time (F^T)	Setup (F^S)
Insertion (F_1^W)	Insertion time (F_1^T)	Insertion Jig (F_1^S)
Sticking (F_2^W)	Sticking time (F_2^T)	Clamp and Pallet (F_2^S)
Caulking (F_3^W)	Caulking time (F_3^T)	Guiding Jig (F_3^S)

The supply chain entities consist of eight supply entities ($S_1^S \sim S_8^S$), seven manufacturing entities ($S_1^M \sim S_7^M$) and four distribution entities ($S_1^D \sim S_4^D$). These supply and manufacturing entities are located globally, and each entity is responsible for supplying/assembling/distributing certain types of components/sub-assembly/finish product. The location, function, capacity and inventory level of the entities in the custom electrical motor supply chain are summarized in Table 4.3.

Table 4.3 Supply chain entity classes

Entity	Location	Component	Capacity	Inventory
S_1^S	Vaasa	C_2^P	700	120
S_2^S	Munich		550	100
S_3^S	Warsaw	C_3^P	750	140
S_4^S	New Delhi		600	110
S_5^S	Vaasa	C_4^P	850	130
S_6^S	Helsinki		650	100
S_7^S	Oulu	C_1^P	800	150
S_8^S	Helsinki		700	120
S_1^M	Vaasa	C_6^S	480	60
S_2^M	Oulu		420	50
S_3^M	Vaasa	C_5^S	600	80
S_4^M	Tampere		500	60
S_5^M	Vaasa	C_7^D	300	40
S_6^M	Munich		350	45
S_7^M	Helsinki		400	50
S_1^D	Finland	C_7^D	600	60
S_2^D	Belgium		1000	100
S_3^D	USA		900	80
S_4^D	Singapore		550	45

4.4.2 VSC Establishment

The VSC is constructed through the procedural definition of customer requirements in RFQ, product family, routings, and supply chains. Under the custom product environment, each customer's RFQ requirements might be different and can propagate as different product configurations in the product domain. In turn, the product is assembled following the routings and procedure defined in the process domain. The logistics partner or distribution centers (DCs) are selected in supply chain domain based on customer location and delivery schedule requirements in RFQ.

The product family and routing classes are organized in a GPPS as shown in Figure 4.7. In this case, the custom motor product items (I_i) correspond to the components classes, i.e., $I_1 = C_1^P$, $I_2 = C_2^P$, $I_3 = C_3^P$, $I_4 = C_4^P$, $I_5 = C_5^S$, $I_6 = C_6^S$, and $I_7 = C_7^D$. The operations in the routing classes are denoted as insertion $U_1 = \langle F_1^W, F_1^T, F_1^S \rangle$, sticking $U_2 = \langle F_2^W, F_2^T, F_2^S \rangle$, and caulking $U_3 = \langle F_3^W, F_3^T, F_3^S \rangle$. The Q_i information beside each component class indicates the material quantity needed to assemble the finish custom product, which is similar to the material 'per' information in the BOM.

Figure 4.7 Product family class and routing classes organized as a GPPS

For illustration purpose, we simplify the supply chain structure by selecting one layer component class only. Of course, this product family and routing class methodology can be propagated into multiple layers component classes' structure using sub-set concept in cases that are more complex.

Next, the VSC is established to accommodate the supply and distribution of materials within and outside the assembly plants. Based on the material requirement and production capacity, a virtual supply chain network structure is established as shown in Figure 4.8.

Figure 4.8 Motor virtual supply chain network

Each node in Figure 4.8 stands for a supply chain entity. The VSC network contains a total of 19 entities: $\Lambda = \Lambda^S \cup \Lambda^M \cup \Lambda^D$, where

$$\Lambda^S = \{S_1^S, S_2^S, S_3^S, S_4^S, S_5^S, S_6^S, S_7^S, S_8^S\} \quad \Lambda^M = \{S_1^M, S_2^M, S_3^M, S_4^M, S_5^M, S_6^M, S_7^M\},$$

and $\Lambda^D = \{S_1^D, S_2^D, S_3^D, S_4^D\}$ denotes the subsets of supplier, manufacturer, and distribution center (DC) entities, respectively. There is logistics cost involved in distribution stage, whereby customer is served by DC closest to their location and the choice of different transportation mode from final assembly factory to DC depends on whether the transportation mode and cost can meet customer RFQ's target cost and delivery schedule requirements or not. The material flow class (Γ) represents material transferring sequence between entities. It is defined with respect to the set of components, i.e.,

$$\Gamma = \{Base, Rotor, Stator, Shield, Case, Drive, Motor\} = \{C_1^P, C_2^P, C_3^P, C_4^P, C_5^S, C_6^S, C_7^D\}$$

By adding the precedence relationship ($\succ_2$) between supply chain entities, with the material requirement, the VSC is defined as:

$$V = \left\{ \begin{array}{l} (S_1^S \succ_2 S_1^M, C_2^P), (S_1^S \succ_2 S_2^M, C_2^P), (S_2^S \succ_2 S_1^M, C_3^P), (S_2^S \succ_2 S_2^M, C_3^P), (S_3^S \succ_2 S_1^M, C_3^P), \\ (S_3^S \succ_2 S_2^M, C_3^P), (S_4^S \succ_2 S_2^M, C_3^P), (S_5^S \succ_2 S_3^M, C_4^P), (S_5^S \succ_2 S_4^M, C_4^P), (S_6^S \succ_2 S_3^M, C_4^P), \\ (S_6^S \succ_2 S_4^M, C_4^P), (S_7^S \succ_2 S_4^M, C_1^P), (S_8^S \succ_2 S_3^M, C_1^P), (S_8^S \succ_2 S_4^M, C_1^P), (S_1^M \succ_2 S_5^S, C_6^S), \\ (S_2^M \succ_2 S_5^S, C_6^S), (S_2^M \succ_2 S_6^M, C_6^S), (S_2^M \succ_2 S_7^M, C_6^S), (S_3^M \succ_2 S_5^S, C_5^S), (S_3^M \succ_2 S_6^M, C_5^S), \\ (S_3^M \succ_2 S_7^M, C_5^S), (S_4^M \succ_2 S_6^M, C_5^S), (S_4^M \succ_2 S_7^M, C_5^S), (S_5^M \succ_2 S_1^D, C_7^D), (S_5^M \succ_2 S_2^D, C_7^D), \\ (S_6^M \succ_2 S_2^D, C_7^D), (S_6^M \succ_2 S_3^D, C_7^D), (S_7^M \succ_2 S_3^D, C_7^D), (S_7^M \succ_2 S_4^D, C_7^D) \end{array} \right\}$$

4.4.3 VSC Configuration and Validation

After the virtual supply chain has been constructed for custom product RFQ response problem, another important issue naturally emerged is how to configure the generic structure into a specific solution to meet the individual customer RFQ requirements. A series of structure formalisms based on object-oriented method have been developed to address this issue. They precisely and systematically represent the constituent elements, structure bonds, and behavior mechanism during virtual supply chain configuration. The detail problems are identified as formulating virtual supply

chain configuration and modeling the static generic supply chain structure with dynamic configurations.

As VSC members are independent and geographically distributed, it is necessary to develop an intelligent information platform to support VSC integration and coordination. An object-oriented platform is proposed to facilitate the handling of the entire lifecycle of a VSC, encompassing its initiation, formation, operation and coordination.

After the VSC model is established, it is used to manage the demand and supply to fulfill customer RFQ requirements and following order requirements in a rapid and cost-effective way. The VSC configuration and validation process automatically generates quotation response for custom products. A specific set of customer RFQ requirements is described as : $O^* = \langle O^{D^*}, O^{Q^*}, O^{L^*}, O^{C^*}, O^{T^*} \rangle$. As an example, the customer RFQ requirements arrive for a custom product of motor $C_7^{D^*1}$, which are specified in details as shown in Table 4.4.

Table 4.4 Customer RFQ requirements for custom motor

Requirements	O^{*1}
Product Spec. (O^{D^*})	(4500rpm, anti-dust, overload protection)
Quantity (O^{Q^*})	310 pieces
Location (O^{L^*})	Seattle, USA
Target Cost (O^{C^*})	50
Lead time (O^{T^*})	45 days

The specific set of customer RFQ requirements is deployed to all the supply chain entities and result in specific supply chain configurations. Moreover, to validate the performance of the supply chain configuration, a web-based logistics management system called agile supply demand network (ASDN) (Helo *et al.*, 2006) is used to model the supply network (Figure 4.9). Based on methodology of object-oriented

class definition mentioned in section 4.4.1 and the virtual supply chain network defined by product manufacturing process and routing in section 4.4.2, ASDN is used as a tool to facilitate those definition of classes and the custom motor virtual supply chain network shows in Fig 4.8.

Figure 4.9 Supply demand network of motor product

A final supply configuration is depicted in Table 4.6 and Fig 4.10 shows the selected VSC configuration which can meet customer RFQ requirements. By simulation based on actual data from case company, the performance of the supply chain is evaluated; where the expected total cost/price of custom motor product, the lead-time in each process and whether can meet customer delivery schedule requirement in RFQ can be computed based on VSC structure shows in Table 4.7.

We have pointed out that the foundation of generic variety configuration originates from object-oriented modeling. Every element specified in a supply chain can be treated as an instance of the generic class item. The instance of an object encompasses all static properties of the object as well as the dynamic ever-changing values of these properties. Thus, these generic items are assumed to align with the objects in object-oriented modeling, a concept of variety state should also hold true in playing a similar role in indirect identification of individual variants from generic items.

There is logistics cost consideration in the distribution stage, i.e. the transportation from final assembly factory to the distribution center (DC) which is located nearest to the customer location and most convenient to serve the customer. We need to select the suitable transportation model under the consideration that it can meet both the target cost and delivery schedule in customer RFQ requirements.

For example, in this case study, there are three different shipping modes to choose from in the distribution stage, which show in below Table 4.5. Finally, the transportation mode of normal air shipment is selected, because the sea shipment takes too long transit time that cannot meet customer delivery schedule requirement and express air shipment costs too much which exceed customer target cost in RFQ requirements.

Table 4.5 Shipping Modes in Distribution Stage

Option Number	Shipping Modes	Transportation Cost/Piece (€)	Transportation Time (Days)
1	Normal air shipment	10	3
2	Sea shipment	3	30
3	Express air shipment	25	1

Table 4.6 Supply chain configuration

Category	Entity	Include	Component	Unit cost (€)	Downstream	Quantity	Lead time
Supply	S_1^S	False	-	-	-	-	-
	S_2^S	True	Rotor C_2^{P*1}	2.3	S_2^M	310	9
	S_3^S	False	-	-	-	-	-
	S_4^S	True	Stator C_3^{P*1}	3.3	S_2^M	310	16
	S_5^S	True	Shield C_4^{P*1}	1.5	S_3^M	50	7
	S_6^S	True	Shield C_4^{P*1}	1.5	S_3^M	160	5
					S_4^M	100	5
	S_7^S	False	-	-	-	-	-
Assembly	S_8^S	True	Base C_1^{P*1}	1.0	S_3^M	210	4
	S_1^M	False	-	-	S_4^M	100	4
					-	-	-
	S_2^M	True	Drive C_6^{S*1}	8.1	S_6^M	250	24
	S_3^M	True	Case C_5^{S*1}	4.6	S_7^M	60	24
					S_6^M	150	10
	S_4^M	True	Case C_5^{S*1}	3.7	S_7^M	60	10
					S_6^M	60	14
Distribution	S_5^M	True	Motor C_7^{D*1}	15	S_3^D	250	32
	S_6^M	False	-	-	-	-	-
	S_7^M	True	Motor C_7^{D*1}	14	S_3^D	60	38
	S_1^D	False	-	-	-	-	-
	S_2^D	False	-	-	-	-	-
	S_3^D	True	Motor C_7^{D*1}	44.8	NA	310	41
	S_4^D	True	-	-	-	-	-

Figure 4.10 VSC configuration result for custom motor product RFQ

Table 4.7 Quotation Response Result

Customer RFQ	Customer Request	Quotation Response
Product Spec.	(4500rpm, anti-dust, overload protection)	(4500rpm, anti-dust, overload protection)
Quantity	310	310
Location	Seattle , USA	Seattle , USA
Price (€)	50	44.8
Lead time (days)	45	41

4.5 Summary

The custom product quotation response process for customer requirements fulfillment involves a series of mapping from the customer domain to the logistics domain with the quotation product specification, quantity, cost and delivery schedule to customer location concerns. Through which decisions with respect to tradeoffs of various supply chain configuration objectives and criteria are analyzed consistently. The final supply chain configuration is selected as the one that lead to optimal or near-optimal results in terms of the selected criteria.

To shed light on practical validations of the VSC configuration methodology, a case study of a global motor quotation response problem is developed based on the domain based structures and class concept. After the VSC is established, it is used to manage the demand/supply for fulfilling customer quotation requests in a rapid and cost-effective way. This is the VSC configuration and validation process. To validate the performance of the supply chain configuration, a web-based logistics management system called agile supply demand network (ASDN) (Helo *et al.*, 2006) is used to model the supply network.

The above simulation result presents the conclusion that the final VSC configuration result in Fig. 4.10 for custom motor product RFQ problem is a subset of motor virtual supply chain network shows in Fig. 4.8. The finish custom motor

product is delivered to customer via the USA distribution center, which is the most approximate to customer location.

CHAPTER 5 DISCUSSION AND FUTURE RESEARCH

This chapter summarizes the research work studied in the dissertation, highlights the important findings and significance of this research. The future research directions and plan are proposed to shed light on follow-up studies of VSC in custom product quotation response VSC configuration.

5.1 Research Summary

The VSC is inherently complex due to its high variety in the product, process and the multi-layer nested supply chain network. Product differentiation inevitably leads to an exponentially increased number of process variations, involving machines, tools, fixtures, setups, cycle times, and labor (Wortmann *et al.*, 1997). The demand of large process variations results in the proliferation of supply entities, which increase the complexity of supply chain network. Moreover, recent green supply chain movement drives for recycle, reuse, *reverse logistics* and *reverse manufacturing* activities in the supply chain, which result in reverse direction material flow and new manufacturing needs and processes.

This research proposes an integrated method to study the problem of custom product quotation response and deal with the high variety issues in supply chain configuration. The generic perspective of VSC configuration establishes the theoretical foundation for supply chain configuration in the custom product environment, where business success relies largely on enterprises' ability to re-configure the supply network rapidly with respect to diverse customer needs.

A domain-based framework is used to handle the complexity and varieties in custom product supply chain configuration. The domain-based reference model provides a systematic viewpoint of supply chain configuration by identifying the key factors related to supply chain variety. Although the configuration of global custom product supply chains encompasses much more issues than showcased in the case study, the fundamental ideas of VSC configuration has been demonstrated and a few interesting issues are examined.

CSP methodology is developed to support coordination of decisions of product, process and supply chain. The VSC classes together with product family classes and routing classes effectively capture the varieties inherent in the global supply chains. By specifying the characteristics of supply entities, the material flows between them, and the precedence relationships, the VSC establishes a generic network structure to address the comprehensive supply chain requirements due to product and process varieties. In addition, using the domain-based rationale, the VSC can be established in a straightforward way, namely, it reflects the product and process structures. It provides a common platform for coordinating decisions associated with the products, processes and supply chains.

The representation rigor of VSC classes makes it convenient to include ICT support to supply chain configuration by using object-oriented concept. In this research, the ASDN software is tailored to the requirements of VSC modeling and analysis. This tool can be used to analyze and visualize the performance of entire supply demand network such as cost, lead-time, capacity throughput, etc. Based on the analysis results, bottlenecks can be identified and alternative solutions can be suggested.

5.2 Future Research

A clear understanding of product and process structure is a prerequisite for using VSC to configure supply chain varieties. For the products with already known design, there is no problem to have predefined BOM structure, product, processes and suppliers in requirements to facilitate VSC configuration. However, the tradeoff among different and potential conflict goals to meet customer requirements in quotation response problem is an interesting topic to study further. For example, how the alternative product structure or manufacturing process will affect cost and lead-time commitment for quotation response.

Another area, which we plan to explore further, is to implement this integrated quotation response method into more complex real case scenarios. Although the case study in this dissertation is from real case, it only studies product structure at a rather abstract level instead of going into much more detail and complex level, which is closer to real cases.

In addition, the optimal configuration of VSC is obtained from all the candidate solutions. Considering different weighting parameters setting for landed price/cost and delivery lead-time in customer RFQ requirements, the same supply chain network may produce different outputs, which can meet the same set of customer RFQ requirements and yet emphasis on different aspects of landed price/cost or delivery lead-time based on weighting parameters. Evaluations might carry out with multiple criteria and different weighting parameter setting on landed price/cost and delivery lead-time for a full simulation case.

Future work might improve the VSC configuration framework by taking a closer look at customer quotation requirements and focal company capability to meet

these requirements. This might allow specific features of VSC configuration to be identified in more details in future.

REFERENCES

Aissaoui, N., Haouaria, M., Hassinib E., (2007), Supplier selection and order lot sizing modeling: A review, *Computers & Operations Research* 34 (2007) 3516 – 3540.

Al-Mashari, M., and Zairi, M. (2003). Supply chain re-engineering using enterprise resource planning software of a SAP R/3 implementation case. *International Journal of Physical Distribution and Logistics Management*, 30(3/4), 296-313.

Ángel García-Crespo, Belén Ruiz-Mezcua, José Luis López-Cuadrado and Israel González-Carrasco (2009), A review of conventional and knowledge based systems for machining price quotation, *Journal of Intelligent Manufacturing*, Volume 22, Number 6, 823-841, DOI: 10.1007/s10845-009-0335-1

Blackhurst, J., Wu, T., and O’Grady, P. (2005). PCDM: a decision support modeling methodology for supply chain, product and process design decisions. *Journal of Operations Management*, 23(3/4), 325-343.

Bullinger, H.J., Lentjes, H.P., and Scholtz, O.H. (2000). Challenges and chances for innovative companies in a global information society. *International Journal of Production Research*, 38(7), 1469-1500.

Caputo, M., Zirpoli, F., (2002), Supplier involvement in automotive component design: outsourcing strategies and supply chain management, *International Journal of Technology Management* 23 (1-3), 129-154.

Chan, F.T.S. and Chan, H.K., (2004), A new model for manufacturing supply chain networks: a multi-agent approach. *Journal of Engineering Manufacture*, 21(8):443-454.

Chien, M. K. and Shih, L. H., (2007), An empirical study of the implementation of green supply chain management practices in the electrical and electronic industry and

their relation to organizational performances, *International Journal of Environmental Science and Technology*, vol:4 iss:3, 383 -394.

Christopher, W.L. (1995). Mass customization: conceptual underpinnings, opportunities and limits. *International Journal of Service Industry Management*, 6(2), 36-45.

Clarke, M.P., (1998), Virtual logistics An introduction and overview of the concepts. *International Journal of Physical Distribution & Logistics Management*, 28(7):486-507.

Clark, D., (1999). What drives companies to seek ISO 14000 certification? *Pollution Engineering*, 14-15.

Cohen, M.A., and Lee, H.L. (1989). Resource deployment analysis of global manufacturing and distribution networks. *Journal of Manufacturing Operations Management*, 2, 81-104.

David Ben-Arieh, Qian Li (2003), Web-based cost estimation of machining rotational parts, *Production Planning and Control*, Vol. 14, Iss. 8, 2003, p778-78

David Ben-Arieh, Qian Li (2008), Parametric cost estimation based on activity-based costing: A case study for design and development of rotational parts, *Int. J. Production Economics*, 113 , 2008, p805-818

Disney S. M., Naim, M.M. and Potter A., (2004), Assessing the impact of e-business on supply chain dynamics. *International Journal of Production Economics*. 89(2):109-118.

Emerson, D. and Piramuthu, S., (2004), Agent-based framework for Dynamic supply chain configuration, *Proceedings of the 37th Hawaii International Conference on System Sciences*.

Er, M. and MacCarthy, B., (2006), Managing product variety in multinational corporation supply chains a simulation study. *Journal of Manufacturing Technology*, 17(8): 1117-1138.

Ferdows, K. (1997). Making the most of foreign factories. *Harvard Business*

Fine, C.H., (1998), *Clockspeed: Winning Industry Control in the Age of Temporary Advantage*. Perseus Books, Reading, MA.

Fine, C.H., Golany, B. and Naseraldin, H. (2005), Modeling tradeoffs in three-dimensional concurrent engineering: a goal programming approach. *Journal of Operations Management*, 23(3-4): 389-403.

Fitzpatrick, W.M. and Burke, D.R., (2000), Form, functions, and financial performance realities for the virtual organization. *SAM Advanced Management Journal*, 65(3): 13-22.

Fixson, S.K., 2005, Product architecture assessment: a tool to link product, process, and supply chain design decisions. *Journal of Operations Management*, 23: 345-369.

Forza, C., and Salvador, F., Rungtusanatham, M., (2005), Coordinating product design, and supply chain design decisions Part A: Topic motivation, performance implications and article review process. *Journal of Operations Management*, Vol. 23, 257-265.

Forza, C., and Salvador, F., Rungtusanatham, M., (2005), Coordinating product design, and supply chain design decisions Part B: Coordinating approaches, tradeoffs, and future research directions, *Journal of Operations Management*, Vol. 23, 319-324.

Forza, C., and Salvador, F., (2002), Product configuration and inter-firm coordination: an innovative solution from a small manufacturing enterprise. *Computers in Industry*, 49(1), 37-46.

- Fox, M.S., Barbuceanu, M., and Teigen, R. (2000). Agent-oriented supply chain management. *International Journal of Flexible Manufacturing Systems*, 12(2/3), 165-188.
- Francas D., Minner S., (2008), Manufacturing network configuration in supply chains with product recovery, *Omega*, Vol 37 (4), 757-769
- Fredriksson, P., (2006), Operations and logistics issues in modular assembly processes: cases from the automotive sector, *Journal of Manufacturing Technology Management*, 17(2): 168-186.
- Galan, R., Racero, J., Eguia, I., and Garcia, J.M. (2007). A systematic approach for product families formation in Reconfigurable Manufacturing Systems. *Robotics and Computer-Integrated Manufacturing*, 23 (5), 489-502.
- Gavimeni S. (2006). Price fluctuations, information sharing, and supply chain performance. *European Journal of Operational Research*. 174(3), 1651-1663.
- Goffin, K., Lemke, F. and Szwejcowski, M. (2006), "An exploratory study of 'close' supplier-manufacturer relationships", *Journal of Operations Management*, Vol.24, No.2, pp. 189-209.
- Graves, S.C. and Willems, S.P. (2003), Optimizing the supply chain configuration for new product, Working paper, Leaders for Management Program and A.P. Sloan School of Management, MIT.
- Gunasekaran A. and E.W.T. Ngai, (2004), Virtual supply-chain management, *Production Planning and Control*, Vol. 15, No. 6, 584-595
- Govindu R., Chinnam R.B., (2007), MASCF: A generic process-centered methodological framework for analysis and design of multi-agent supply chain systems, *Computers & Industrial Engineering*, Vol. 53, (4), 584-609.
- Greis, N. P., and Kasarda, J. D. (1997). Enterprise logistics in the information era. *California Management Review*, 39(3), 55-78.

Gunasekaran, A. and Ngai E. W. T., (2005), Build-to-order supply chain management: a literature review and framework for development, *Journal of Operations Management*, 8(2): 163-182.

Gunasekaran, A., and Ngai E. W. T. (2004). Information systems in supply chain integration and management. *European Journal of Operational Research*, 159(2), 269-295.

Gupta, S., and Krishnan, V. (2001). Appropriateness and Impact of Platform-Based Product Development, *Management Science*, Vol 47, 2001, 52-68.

Handfield, R.B. (1994). US global sourcing: patterns of development. *International Journal of Operations and Production Management*, 14, 40-51.

Hayes, R.H., Wheelright, S.c., (1997), Link manufacturing process and product life cycles, *Harvard Business Review*, 57(1), 133-140.

Hervani, A.A., Helms, M.M., Sarkis, J., (2005), The performance measurement for green supply chain management, *Benchmarking: An International Journal*, Vol 12, Issue 4, 330-353.

Helo, P., You, X. and Jiao, J., (2006), A web-based logistics management system for agile supply demand network design. *Journal of Manufacturing Technology Management*, 17(8): 1058-1077.

Ho, H.H., Parsael, H.R., Wong, J.P., (1991). Concurrent engineering: the manufacturing philosophy for the 09's. *Computer & Industrial Engineering* 21 (1-4), 35-39.

Houlihan, J.B., (1985), International supply chain management. *International Journal of Physical Distribution and Materials Management*, 15(1): 22-38.

- Hsu, C.W., Hu, A.H., (2007), Application of analytic network process on supplier selection to hazardous substance management in green supply chain management, IEEE International Conference on Industrial Engineering and Engineering Management, vol 1-4 : 1362-1368.
- Huang, G.Q., Zhang, X.Y., and Liang, L. (2005). Towards integrated optimal configuration of platform products, manufacturing processes, and supply chains. *Journal of Operations Management*, 23(3-4), 267-290.
- Hult, G.T.M., Swan, K.S., (2003), A research agenda for the nexus of product development and supply chain management processes. *Journal of Product Innovation Management* 20 (6), 427-429.
- Javier, P., Otto, K.N., and Baker, J. D. (2000). A method for architecting product platforms. *Research in Engineering Design*, 12(2), 61-72.
- Jayaraman, V., (1998), Transportation, facility location and inventory issues in distribution network design. *International Journal of Operations and Production Management*, 18(5): 471-494.
- Jiao, J.X. Tseng M. Mitchell, Duffy Vincent G. , Lin Fuhua, (1998), Product family modeling for mass customization, *Computers and Industrial Engineering*, Vol. 35, Issue 3-4, 495-498
- Jiao, J., and Tseng, M.M. (1999). A pragmatic approach to product costing based on standard time estimation. *International Journal of Operations and Production Management*, 19(7), 738-755.
- Jiao, J., Tseng, M.M., Ma, Q. and Zou, Y., (2000), Generic bill of materials and operations for high-variety production management, *Concurrent Engineering: Research and Applications*, 8(4). 297-322.
- Jiao, J.X., and Tseng, M.M. (2004). Customizability analysis in design for mass customization. *Computer Aided Design*, 36(8), 745-757.

- Jiao, J., Zhang, L.; Pokharel, S., (2007), Process platform planning for variety coordination from design to production in mass customization manufacturing. *IEEE Transactions on Engineering Management*, 54(1):112-129.
- Jin, M., Luo, Y., and Eksioglu, S.D.,(2008), Integration of production sequencing and outbound logistics in the automotive industry, *International Journal of Production Economics*, 113:766-774.
- Kern, G.M., Guerrero, H.H., (1990), A conceptual model for demand management in the assemble-to-order environment, *Journal of Operations Management*, Vol 9, Issue 1, 65-84.
- Kim, B., Leung, J.M.Y., Park, K.T., Zhang, G., and Lee, S. (2002). Configuring a manufacturing firm's supply network with multiple suppliers. *IIE Transactions*, 34(8), 663-677.
- King, B.E., Benton, W.C., (1987), Alternative master production scheduling techniques in an assemble-to-order environment, *Journal of Operations Management*, Vol 7, Issues 1-2, 179-201
- Lee, H.L., and Billington, C. (1993). Material management in decentralized supply chains. *Operations Research*, 41(5), 835-847.
- Lee, H.L., and Tang, C.S. (1997). Modeling the cost and benefits of delayed product differentiation. *Management Science*, 43(1), 40-53.
- Lee, H.L., and Tang, C.S. (1998). Variability reduction through operations reversal. *Management Science*, 44, 162-173.
- Leenders, M.R., Fearon, H.E., Flynn, A.E., and Johnson, P.F. (2002). *Purchasing and Supply Management*. McGraw-Hill Irwin, Boston, MA.
- Lewis, L. (1999). CPFR: One giant business plan. *Progressive Grocer* (April), 69-72.

Lin, F.R., and Shaw, M.J. (1998). Reengineering the order fulfillment process in supply chain networks. *The International Journal of Flexible Manufacturing Systems*, 10, 197-225.

Magro, D., and Torasso, P. (2003). Decomposition strategies for configuration problems. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, 17(1), 51-73.

Mayer, M., and Utterback, J. (1993). The product family and the dynamics of core capability. *Sloan Management Review*, Spring, 29-47.

Min, H., and Zhou, G. (2002). Supply chain modeling: past, present and future. *Computers and Industrial Engineering*, 43, 231-249.

Min, H., and Melachrinousdis, E. (1999). The relocation of a hybrid manufacturing/distribution facility from supply chain perspectives: A case study. *Omega*, 27(1), 75-85.

Monk, Ellen; Wagner, Bret (2007). *Concepts in Enterprise Resource Planning*. Course Technology Cengage Learning. 97-98.

Ng, N.K. and Jiao, J., (2004), A domain-based reference model for the conceptualization of factory loading allocation problems in mulit-site manufacturing supply chains. *Technovation*, 24:631-642.

Noori, H and Lee, W.B., 2006, Dispersed network manufacturing: adapting SMEs to compete on the global scale. *Journal of Manufacturing Technology Management*, 17(8): 1022-1041.

Peterson, J.L. (1977). Petri Nets. *Computing Surveys*, 9(3), 223-252.

Peterson, J.L. (1981). *Petri Net Theory and the Modeling of Systems*. Prentice-Hall, Englewood Cliffs, N.J.

- Petersen, S.A., Divitini, M., and Matsken, M. (2001). An agent-based approach to modeling virtual enterprises. *Production Planning and Control*, 12(3), 224-233.
- Patterson, K.A., Grim, C.M., and Corsi, T.M. (2003). Adopting new technologies for supply chain management. *Transportation Research Part E: Logistics and Transportation Review*, 39(2), 95-121.
- Petersen K.J., Handfield R.B., Ragatz G.L., (2005), Supplier integration into new product development: coordinating product, process and supply chain design, *Journal of Operations Management*, 23, 371-388.
- Partanen, G.N., Greis, N.P., and Kasarda, J.D. (2006). Logistics, strategy and structure. *International Journal of Operations and Production Management*, 18(1), 37-52.
- Pine, J.B. (1993). *Mass Customization: the New Frontier in Business Competition*. Harvard Business School Press, Boston.
- Piramuthu S. (2005), Knowledge-based framework for automated dynamic supply chain configuration, *European Journal of Operational Research* 165 (1) 219-230
- Piramuthu S. (2005), Machine learning for dynamic multi-product supply chain Formation, *Expert System Application* 29 (4) 985-990
- Pontrandolfo, P., and Okogbaa, O.G. (1999). Global manufacturing: a review and a framework for planning in a global corporation. *International Journal of Production Research*, 37(1), 1-19.
- Pontrandolfo, P., Gosavi, A., Okogbaa, O.G., and Das, T.K. (2002). Global supply chain management: a reinforcement learning approach. *International Journal of Production Research*, 40(1), 1299-1317.
- Porter, M.E., (1986), Changing patterns of international competition. *California Management Review*, XXVIII(2): 9-40

- Rohde, J. (2000). *Coordination and Integration of Supply Chain Management*. Springer-Verlag, Berlin.
- Rudberg, M., and West B.M. (2006). Global operations strategy: Coordinating manufacturing networks. *Omega*, 36 (1), 91-106.
- Sabin, D., and Weigel, R. (1998). Product configuration frameworks: a survey. *IEEE Intelligent Systems*, 13(4), 42-49.
- Sadeh, N.M., Hildum, D.W., Kjenstad, D., and Tseng, A. (2001). MASCOT: an agent-based architecture for dynamic supply chain creation and coordination in the internet economy. *Production Planning and Control*, 12(3), 212-223.
- Salvador, F., Rungtusanatham, M., and Forza, C. (2004). Supply chain configurations for mass customization. *Production Planning and Control*, 15 (4), 381-397.
- Sanderson, S.W., and Uzumeri, M. (1997). *Managing Product Families*. Irwin, Chicago.
- Sathi, N., Fox, M.S., Goyal, R. and Kott, A.S., (1992), Resource configuration and allocation - a case study of constrained heuristic search. *IEEE Expert*, 7(2): 26 - 35.
- Scott, C. and Westbrook, R., (1991), New strategic tools for supply chain management, *International Journal of Physical Distribution and Logistics Management*, 21:1, 22-23.
- Serve, M., Yen, D. C. and Wang, J.C., (2002), B2B enhanced supply chain process: toward building virtual enterprises. *Business Process Management Journal*, 8(3): 245-253.
- Shawn, R., (2008), A larger serving of greens, *Modern Healthcare*; 8/4/2008, Vol. 38 Issue 31, 28-30,

Sherman, R.J. (1998). Collaborative planning forecasting and replenishment: realizing the promise of efficient consumer response through collaborative technology. *Journal of Marketing Theory and Practice*, 6, 6-9.

Stadzisz, P.C., and Henrioud, J.M. (2005). Integrated design of product families and assembly systems. *Proceedings of IEEE International Conference on Robotics and Automation*, 1290-1295.

Stratton, R., and Warburton, R.D. (2006). Managing the trade-off implications of global supply. *International Journal of Production Economics*, 103 (2), 667-679.

Swaminathan, J.M., Smith, S.F., and Sadeh, N.M. (1996). A multi-agent framework for modeling supply chain dynamics. *Proceedings of NSF Research Planning Workshop on Artificial Intelligence and Manufacturing*, Albuquerque, NM, 103-108.

Swaminathan, M.M., and Tayur, S.R. (1999). Stochastic programming models for managing product variety. *Quantitative models for supply chain management*, Kluwer Academic Publishers, Boston, MA.

Swaminathan, M.M., and Tayur, S.R. (2003), Models for supply chain in e-business, *Management Science*, 49(10), 1387-1406.

Suh, N.P. (2001). *Axiomatic Design-Advances and Applications*. Oxford University Press, New York.

Thomas, J.P., Nissanke, N., and Baker, K.D. (1996). A hierarchical Petri net framework for the representation and analysis of assembly. *IEEE Transactions on Robotics and Automation*, 12(2), 268-279.

Thomas J. Graser, Brian J. McGiverin and K. Suzanne Barber, (1997), A supply chain configuration tool, *Proceedings of 1997 ASEM Design engineering technical conference*, Sept 14-17, Detc97-CIE-4293

Timothy, W. Simpson, (2004), Product platform design and customization: Status and promise. *Artificial Intelligence For Engineering Design Analysis & Manufacturing*, Volume 18, Number 1 (January 2004), 3-20.

Tseng, M.M., and Jiao, J.X. (1998). Concurrent design for mass customization. *Business Process Management Journal*, 4(1), 10-24.

Tu Hoang Truong and Farhad A., (2003), Simulation based optimization for supply chain configuration design, *Proceedings of the 2003 winter simulation conference*.

Ulrich, K., and Eppinger, S.D. (1995). *Product Design and Development*. McGraw-Hill Inc, NJ.

Ulrich, K., and Tung, K. (1991). Fundamentals of product modularity. *Proceedings of ASME Winter Annual Meeting Conference*, Atlanta.

Van Hoek, R., (2001), E-supply chains – virtually non-existing. *Supply Chain Management: An International Journal*, 6 (1): 21-28.

Veeramani, Dharmaraj and Joshi, Pawan, Methodologies for rapid and effective response to requests for quotation (RFQs), *IIE Transactions*, 1997, 29(10), p825-838

Vickery, S.K., Jayaram, J., Doroge, C., and Calantone, R. (2003). The effects of an integrative supply chain strategy on customer service and financial performance: an analysis of direct versus indirect relationships. *Journal of Operations Management*, 21(5), 523-539.

Wang, C.X., and Benaroch, M. (2004). Supply chain coordination in buyer centric B2B electronic market. *International Journal of Production Economics*, 92, 113-124.

Wemmerlov, V. (1984), Assemble-to-order manufacturing: implications for materials management, *Journal of Operations Management*, 4(4), 347-368

Whitney, D.E. (1993). Nippondenso Co. Ltd: A case study of strategic product design. *Research in Engineering Design*, 5(1), 1-20.

Wezel, W.V., Donk, D.P.V., Gaalman, G., (2006) The planning flexibility bottleneck in food processing industries, *Journal of Operations Management*, Vol 24, Issue 3, 287-300

Wisner, J.D., Tan, K.C., (2000), Supply chain management and its impact on purchasing, *Journal of Supply Chain Management*, Fall 2000, 36,4, 33-42.

Wongvasu, Naken (2001), Methodologies for providing rapid and effective response to request for quotation (RFQ) of mass customization products, PhD thesis, Northeast University

Wood, D.F., Barone, A.P., Murphy, P.R., and Wardlow, D.L. (2002). *International Logistics*. AMACOM, New York.

Wortmann, J.C., Hegge, H.M.H., Rolefes, S., (1997), Embedding enterprise software in extended enterprise models, *Computers in Industry*, 42(2-3), 231-243.