

# **Process Modeling, Performance Analysis and Configuration Simulation in Integrated Supply Chain Network Design**

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Keywords: Process modeling, performance analysis, configuration simulation, integrated  
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## **(ABSTRACT)**

Supply chain management has been recently introduced to address the integration of organizational functions ranging from the ordering and receipt of raw materials throughout the manufacturing processes, to the distribution and delivery of products to the customer. Its application demonstrates that this idea enables organizations to achieve higher quality products, better customer service, and lower inventory cost.

In order to achieve high performance, supply chain functions must operate in an integrated and coordinated manner. Several challenging problems associated with integrated supply chain design are: (1) how to model and coordinate the supply chain business processes, specifically in the area of supply chain workflows; (2) how to analyze the performance of an integrated supply chain network so that optimization techniques can be employed to improve customer service and reduce inventory cost; and (3) how to evaluate dynamic supply chain networks and obtain a comprehensive understanding of decision-making issues related to supply network configurations. These problems are most representative in the supply chain theory's research and applications.

There are three major objectives for this research. The first objective is to develop viable modeling methodologies and analyzing algorithms for supply chain business processes so that the logic properties of supply chain process models can be analyzed and verified. This problem has not been studied in integrated supply chain literature to date. To facilitate the modeling and verification analysis of supply chain workflows, an object-oriented Petri nets based modular modeling and analyzing approach is presented. The proposed, structured, process-modeling algorithm provides an effective way to design structured supply chain business processes.

The second objective is to develop a network of inventory-queue models for the performance analysis and optimization of an integrated supply network with inventory control at all sites. An inventory-queue is a queueing model that incorporates an inventory replenishment policy for the output store. This dissertation extends the previous work done on the supply

network model with base-stock control and service requirements. Instead of one-for-one base stock policy, batch-ordering policy and lot-sizing problems are considered. In practice, the assumption of uncapacitated production is often not true, therefore,  $GI^x/G/1$  queueing analysis is used to replace the  $M^x/G/\infty$  queue based method. To determine the replenishment lead times of items at the stores, a fixed-batch target-level production authorization mechanism is employed to explicitly obtain performance measures of the supply chain queueing model. The validity of the proposed model is illustrated by comparing the results from the analytical performance evaluation model and those obtained from the simulation study.

The third objective is to develop simulation models for understanding decision-making issues of the supply chain network configuration in an integrated environment. Simulation studies investigate multi-echelon distribution systems with installation stock reorder policy and echelon stock reorder policy. The results show that, depending on the structure of multi-echelon distribution systems, either echelon stock or installation stock policy may be advantageous. This dissertation presents a new transshipment policy, called “alternate transshipment policy,” to improve supply chain performance. In an integrated supply chain network that considers both the distribution function and the manufacturing function, the impacts of component commonality on network performance are also evaluated. The results of analysis-of-variance and Tukey’s tests reveal that there is a significant difference in performance measures, such as delivery time and order fill rates, when comparing an integrated supply chain with higher component commonality to an integrated supply chain with lower component commonality.

Several supply chain network examples are employed to substantiate the effectiveness of the proposed methodologies and algorithms.

**Keywords:** Process modeling, performance analysis, configuration simulation, integrated supply chain network design

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# TABLE OF CONTENTS

<b>Chapter 1 Introduction</b> .....	<b>1</b>
1.1 Background and Motivation .....	1
1.1.1 Supply Chain “Definition” .....	1
1.1.2 Functions and Tasks of Supply Chain Management.....	3
1.1.3 Bullwhip Effect in Supply Chains .....	4
1.1.4 Supply Chain Modeling Approaches .....	4
1.1.5 Demand Response Strategies in Supply Chain Management.....	7
1.1.6 Product Variety, Postponement and Process Sequencing in Supply Chain ...	9
1.1.7 Supply Chain Network Configuration.....	11
1.2 Problem Statement and Research Objectives .....	14
1.2.1 Process Modeling in Integrated Supply Chain Design .....	14
1.2.2 Performance Analysis of Integrated Supply Chain Networks.....	19
1.2.3 Simulation Modeling and Analysis for Integrated Supply Chain Network Configurations .....	21
1.3 Research Approach.....	23
1.4 Contributions of the Research.....	25
1.5 Organization of the Dissertation.....	26
<b>Chapter 2 Literature Review</b> .....	<b>28</b>
2.1 Literature Review on Supply Chain Business Processes and Workflows .....	28
2.1.1 Design of Supply Chain Processes.....	28
2.1.2 Verification Analysis of Supply Chain Workflows .....	30
2.2 Literature Review on Multi-Stage Production-Inventory-Distribution Supply Chain Networks.....	31
2.3 Literature Review on Simulation of Integrated Supply Network Configurations .....	36
2.3.1 Simulation in Supply Chain Management.....	36
2.3.2 Lateral Transshipment in Multi-Echelon Distribution Systems .....	38
2.3.3 Component Commonality in Supply Chain Networks.....	38

<b>Chapter 3 Structured Business Process Design of Supply Chain Processes .....</b>	<b>40</b>
3.1 Constructs of the Function View .....	41
3.1.1 Process Models of CIMOSA .....	41
3.1.2 Business Process Entity Definition .....	41
3.1.3 Manufacturing Enterprise Behavior Specification.....	41
3.1.4 Manufacturing Enterprise Functionality Specification .....	42
3.2 Supply Chain Business Process Design .....	43
3.2.1 Motivation .....	43
3.2.2 Well-behaved Routing Structures in Supply Chain Processes .....	44
3.2.3 Structured Supply Chain Business Processes .....	47
3.3 Structured Supply Chain Business Process Modeling Algorithm .....	49
3.4 An Application Example.....	55
3.5 Free-choice Process-nets with Event Extension .....	58
3.6 Summary .....	59
<b>Chapter 4 Verification Analysis and Reengineering of Supply Chain Workflows Using Object-Oriented Petri Nets.....</b>	<b>60</b>
4.1 Basics of Supply Chain Workflows .....	60
4.1.1 Components of Supply Chain Work Units.....	61
4.1.2 Components of Supply Chain Workflow Channels.....	61
4.2 A Manufacturing Supply Chain Case.....	62
4.3 OPTN (Object Predicate/Transition Net) Model.....	63
4.3.1 Top-level Model and Object-level Model.....	63
4.3.2 Verification Analysis of Supply Chain Workflow Processes.....	66
4.3.3 System P-Invariants with Changeable Object Structures.....	72
4.4 Sequencing Analysis of Supply Chain Operations by Net Unfolding .....	72
4.4.1 Process-oriented Modeling of Objects .....	73
4.4.2 A Case Study for Sequencing Analysis by Ordering Relations .....	74
4.5 Summary .....	76

**Chapter 5 An Integrated Framework for Multi-Stage Production-Inventory-Distribution Supply Chain Networks ..... 78**

5.1 Network Topology..... 78  
    5.1.1 Sites and Stores ..... 78  
    5.1.2 Links..... 79  
5.2 The Relationships between Stores ..... 81  
    5.2.1 Inventory Positions within Stores ..... 82  
    5.2.2 Nominal and Actual Replenishment Lead Times of Stores ..... 82  
    5.2.3 Nominal and Actual Replenishment Lead Times of Sites ..... 84

**Chapter 6 Performance Analysis and Optimization of Multi-Stage Production-Inventory-Distribution Supply Chain Networks ..... 85**

6.1 Information Flows in Supply Chain Networks ..... 85  
    6.1.1 Demand Transmission Process in Supply Chain Networks ..... 86  
    6.1.2 Service Level Transmission in Supply Chain Networks..... 87  
    6.1.3 Product Demands and Target Service Levels..... 88  
6.2 Performance Analysis of a Single-Product-Type Store ..... 89  
    6.2.1 Make-to-Stock Stores..... 89  
    6.2.2 Production Authorization (PA) Cards Control Mechanism ..... 91  
    6.2.3 Performance Analysis with  $GI^x/G/1$  Queue..... 92  
    6.2.4 Optimization of Inventory Positions ..... 100  
    6.2.5 Performance Analysis of a Store..... 100  
6.3 The Optimization Model..... 104  
6.4 Numerical Examples ..... 105  
    6.4.1 Performance Analysis Results ..... 105  
    6.4.2 Optimization Results ..... 109

**Chapter 7 Simulation Modeling and Analysis of Integrated Supply Chain Network Configurations ..... 110**

7.1 A Component based Simulation Modeling Approach ..... 110  
7.2 Stroboscope — A State and Resource based Simulation Language ..... 111  
    7.2.1 Network Elements..... 111

7.3 Some Building Blocks for Simulation Modeling of Supply Chain Networks	112
7.3.1 The Retailers.....	113
7.3.2 The Warehouses.....	114
7.4 Approximate Inventory Analysis for Multi-Echelon Distribution Systems ...	114
7.4.1 Echelon Stock and Installation Stock Policies for Multi-Echelon Distribution Systems.....	115
7.4.2 Sequential Stocking Points with Level Demand.....	116
7.4.3 Lead Time Demand and Re-Order Points Calculation for Serial Situation	119
7.5 Input Parameters for Simulation Models .....	122
7.6 Output Data Analysis for Terminating Simulation Models .....	124
7.6.1 Experimenting with Terminating Simulations.....	124
7.7 Simulation Models and Statistical Analysis for Multi-Echelon Distribution Systems.....	127
7.7.1 Output Analysis of Installation Stock Policy vs. Echelon Stock Policy ....	129
7.7.2 Output Analysis of A Multi-Echelon Distribution System with Lateral Transshipment .....	133
7.8 Component Commonality in Integrated Supply Chain Networks.....	144
7.8.1 Commonality Index (CI) .....	144
7.8.2 Impact of Component Commonality on Integrated Supply Chain Performance.....	146
7.9 Simulation Model Verification and Validation .....	154
7.9.1 Verification.....	154
7.9.2 Validation .....	154
<b>Chapter 8 Conclusions and Future Research.....</b>	<b>155</b>
8.1 Conclusions.....	155
8.2 Future Research Directions.....	157
8.2.1 Supply Chain Business Processes.....	158
8.2.2 Performance Analysis and Optimization in Multistage Supply Chain Networks .....	158
8.2.3 Supply Chain Network Configuration Simulation.....	159

<b>REFERENCES</b> .....	161
<b>APPENDIX A: Some Petri Nets Definitions, Notation and Theorems</b> .....	171
<b>APPENDIX B: Source Code for the Simulation Model of An Integrated Supply Chain Network with Echelon Stock Policy and Commonality Index of 1</b> .....	174
<b>Vita</b> .....	187

## LIST OF FIGURES

Figure 1.1 Customer order decoupling point (courtesy of Higgins, et al., 1996).....	8
Figure 3.1 Supply chain process routing structures and Petri net representations .....	45
Figure 3.2 Free-choice Petri net representations of six well-behaved constructs of supply chain	47
Figure 3.3 An example of asymmetric confusions .....	51
Figure 3.4 Illustrations for Theorem 1 .....	54
Figure 3.5 The four domain processes in a shop floor domain .....	56
Figure 3.6 Behavior analysis diagram of shop floor domain process (Functional decomposition hierarchy).....	56
Figure 3.7 Structured process model development procedure for a shop floor manufacturing domain process.....	57
Figure 4.1 An manufacturing supply chain case .....	62
Figure 4.2 Top-level object model for product line 1 under mode 1.....	63
Figure 4.3 Top-level object model for product line 2 under mode 1.....	63
Figure 4.4 Input ports and output ports of OPTN A.....	64
Figure 4.5 Relations of input and output ports of OPTN A.....	65
Figure 4.6 “1 : many” object interaction.....	67
Figure 4.7 OPTN for vehicle V1 .....	68
Figure 4.8 OPTN for P1 .....	69
Figure 4.9 OPTN for P3.....	70
Figure 4.10 P-invariants for V1, P1 and P3 .....	70
Figure 4.11 Process model of object P3.....	75
Figure 4.12 Unfolding nets of process model for object P3.....	75
Figure 4.13 Gantt chart for the schedule of supply chain process.....	76
Figure 5.1 An integrated framework for multi-stage supply chain networks .....	80
Figure 5.2 Inventory position at a store .....	82
Figure 6.1 The illustration of an demand transmission process .....	87
Figure 6.2 An example of an integrated supply chain network.....	106
Figure 7.1 The modeling block for customer demands .....	113
Figure 7.2 The snapshot for “Consolidator Properties of BatchTransP1C1” .....	113
Figure 7.3 Behavior of the inventory levels in a deterministic two-stage distribution system...	116

Figure 7.4 Simulation model for a multi-echelon distribution system with installation stock reorder point policy .....	128
Figure 7.5 Snapshots for the output of the simulation models.....	129
Figure 7.6 Costs and fill rates for a multi-echelon distribution system with echelon stock reorder point policy .....	131
Figure 7.7 Costs with different warehouse reorder points for a distribution system with installation stock policy vs. echelon stock policy .....	132
Figure 7.8 Fill rates with different warehouse reorder points for a distribution system with installation stock policy vs. echelon stock policy .....	132
Figure 7.9 Simulation model for a multi-echelon distribution system with installation stock reorder point policy and random transshipment policy (Case I).....	135
Figure 7.10 Simulation model for a multi-echelon distribution system with installation stock reorder point policy and alternate transshipment policy (Case I) .....	136
Figure 7.11 Simulation model for a multi-echelon distribution system with installation stock reorder point policy and random transshipment policy (Case II) .....	137
Figure 7.12 Simulation model for a multi-echelon distribution system with installation stock reorder point policy and alternate transshipment policy (Case II).....	138
Figure 7.13 Costs with different warehouse reorder points for a distribution system with different transshipment policies (Case I).....	139
Figure 7.14 Fill rates with different warehouse reorder points for a distribution system with random transshipment policy vs. alternate transshipment policy (Case I).....	140
Figure 7.15 Costs with different warehouse reorder points for a distribution system with different transshipment policies (Case II).....	141
Figure 7.16 Fill rates with different warehouse reorder points for a distribution system without transshipment .....	142
Figure 7.17 Fill rates with different warehouse reorder points for a distribution system with random transshipment policy .....	142
Figure 7.18 Fill rates with different warehouse reorder points for a distribution system with alternate transshipment policy .....	143
Figure 7.19 Computational examples for the degree of commonality index .....	145
Figure 7.20 Simulation model for an integrated supply chain network with echelon stock policy and commonality index of 1 .....	148

## LIST OF TABLES

Table 1.1 Comparison between different demand response strategies.....	9
Table 3.1 CIMOSA behavioral rules for process workflow (ESPRIT Consortium 1993) .....	43
Table 4.1 Routing structure for product line 1 .....	68
Table 4.2 (Functional Operations × Functional Entities) matrix.....	69
Table 4.3 (Functional Operations × Functional Entities) matrix for different products.....	74
Table 7.1 Costs and fill rates with different warehouse reorder points for a distribution system with echelon stock policy .....	129
Table 7.2 Fill rates with different retailer reorder points for a distribution system with echelon stock policy .....	130
Table 7.3 Costs with different warehouse reorder points for a distribution system with installation stock policy vs. echelon stock policy .....	130
Table 7.4 Fill rates with different warehouse reorder points for a distribution system with installation stock policy vs. echelon stock policy .....	130
Table 7.5 Costs with different warehouse reorder points for a distribution system with different transshipment policies (Case I).....	139
Table 7.6 Fill rates with different warehouse reorder points for a distribution system with random transshipment policy vs. alternate transshipment policy (Case I).....	140
Table 7.7 Costs with different warehouse reorder points for a distribution system with different transshipment policies (Case II).....	141
Table 7.8 Fill rates with different warehouse reorder points for a distribution system with random transshipment policy vs. alternate transshipment policy (Case II).....	142
Table 7.9 Simulation results for fill rate, delivery time, and resource utilization rate.....	147
Table 7.10 Analysis-of-variance for delivery time .....	149
Table 7.11 Analysis-of-variance for retailer 1’s fill rate.....	150
Table 7.12 Analysis-of-variance for retailer 2’s fill rate.....	151
Table 7.13 Analysis-of-variance for retailer 3’s fill rate.....	152

# Chapter 1

## Introduction

### 1.1 Background and Motivation

#### 1.1.1 Supply Chain “Definition”

The supply chain management (SCM) literature offers many variations on the same theme when defining a supply chain. The most common definition [Houlihan (1985), Stevens (1989), Lee and Billington (1993), and Lamming (1996)] is *a system of suppliers, manufacturers, distributors, retailers, and customers where materials flow downstream from suppliers to customers, and information flows in both directions.*

A supply chain is also a *network* of facilities and distribution options that functions to procure materials, transform these materials into intermediate and finished products, and distribute these finished products to customers. Supply chains exist in both service and manufacturing organizations, although the complexity of the chain may vary greatly from industry to industry and firm to firm. Realistic supply chains have multiple end products with shared components, facilities and capacities. The flow of materials is not always along an arborescent network; various modes of transportation may be considered, and the bill of materials for the end items may be both deep and large.

Traditionally, marketing, distribution, planning, manufacturing, and the purchasing of organizations along the supply chain operate independently. These organizations have their own objectives and they are often conflicting. Marketing's objectives of high customer service and maximum sales dollars conflict with the manufacturing and distribution goals. Many manufacturing operations are designed to maximize throughput and lower costs with little consideration for the impact on inventory levels and distribution capabilities. Purchasing contracts are often negotiated with very little information beyond historical buying patterns. The result of these factors is that there is not a single, integrated plan for the organization. Clearly,

there is a need for a mechanism through which these different functions can be integrated together. Supply chain management is a strategy through which such an integration can be achieved. Supply chain management is typically viewed to lie between fully vertically integrated firms, where the entire material flow is owned by a single firm, and where each channel member operates independently. Therefore, coordination between the various players to the chain is key in its effective management.

A supply chain may be defined as an integrated process wherein various business entities (i.e., suppliers, manufacturers, distributors, and retailers) work together in an effort to: (1) acquire raw materials, (2) convert these raw materials into specified final products, and (3) deliver these final products to retailers. This chain is traditionally characterized by a forward flow of materials and a backward flow of information.

The current interest has sought to extend the traditional supply chain to include “reverse logistics,” to include product recovery for the purposes of recycling, re-manufacturing, and re-use. Within manufacturing research, the supply chain concept grew largely out of two-stage multi-echelon inventory models. It is important to note that considerable progress has been made in the design and analysis of two-echelon systems.

Towill (1997) argues that the definition needs to be flexible because it “applies right across the business spectrum ranging from international supply chains down to a number of related sequential activities undertaken under one roof but covering a number of independent cost centers.” Houlihan (1985) is credited with first coining the term “supply chain,” but it seems that researchers have varying interpretations of exactly what managing a supply chain means.

Forrester (1961) suggests that the five flows of any economic activity -- *money, orders, materials, personnel, and equipment* -- are interrelated by an information network, which gives the “system,” which has now come to be called a supply chain, its own character.

The common thread in any definition is that supply chain management seeks to integrate performance measures over multiple firms or processes, rather than taking the perspective of a single firm or process. For example, at MIT, the field of SCM is defined as follows:

*“Integrated Supply Chain Management (ISCM) is a process-oriented, integrated approach to procuring, producing, and delivering products and services to customers. ISCM has a broad scope that includes sub-suppliers, suppliers, internal operations, trade customers, retail customers, and end users. ISCM covers the management of material, information, and funds flows.”*

From a multi-agent information system perspective (Lee and Billington, 1993; Swaminathan, et al., 1996), a supply chain network is *a network of autonomous or semi-autonomous business entities involved, through upstream and downstream links, in the different processes and activities that produce physical goods or services to customers.*

### **1.1.2 Functions and Tasks of Supply Chain Management**

Using the concept of flow from raw material to consumer, Mabert and Venkataramanan (1998) presented a general structure of the supply chain and a sample of elements (managerial functions and tasks) that configure it. The chain contains five aggregate or major stages to represent important phases in the flow.

**Sourcing** involves not only the supply of raw materials and components through a network of vendors, it also includes product development support through subassembly design and tooling production for process changes.

**Inbound Logistics** focuses on effective and efficient movement and storage of required materials to meet production schedules.

**Manufacturing** uses provided inputs to produce a high quality and price competitive product in a timely manner.

**Outbound Logistics** concentrates on movement of finished goods through the distribution network to global markets for consumer use.

**After-market Service** recognizes the need to support the product either through repair service, or customer service representatives, to answer product-use questions.

### **1.1.3 Bullwhip Effect in Supply Chains**

Three fundamental sources of uncertainty exist along a supply chain. They are demand (volume and mix), process (yield, machine downtimes, transportation reliabilities), and supply (part quality, delivery reliabilities). The variation in demand propagates upstream in an amplified form (i.e., demand distortion). This is called the bullwhip effect, and it has serious cost implications. Such an effect is a consequence of industrial dynamics or time varying behaviors of industrial organizations and a lack of correct feedback control systems.

The uncertainties in the supply chain network make manufacturing enterprises inefficient. The supply chain management should be concerned with the reduction or even elimination of uncertainties. The traditional way of coping with uncertainties (caused by quality variation, supplier unreliability and unpredictable customer demand in each stage of the supply chain) has been to build inventories or to provide excess capacity. This is costly and inefficient. In addition, the improvement in individual organizations does not necessarily contribute to the improvement of the whole supply chain. Hence, the competition between individual organizations is being replaced by the competition between supply chains. In order to create lean and responsive supply chains, uncertainties that restrict operational performance on the chain level should be systematically and jointly tackled at all stages in the supply chain. Some other improvements that can reduce the bullwhip effect include the reduction of lead times, revising reorder procedures, limiting price fluctuations, and the integration of planning and performance measurement (Lee, et al., 1997).

### **1.1.4 Supply Chain Modeling Approaches**

Generally, modeling approaches in SCM can be categorized into five broad classes.

**Supply Chain Network Design Method:** This method determines the location of production, stocking, and sourcing facilities, and channels the products take through them. The earliest work in this area, although the term “supply chain” was not then in vogue, was by Geoffrion and Graves (1974). They introduced a multi-commodity, logistics network design

model for optimizing finished product flows from plants, to the distribution centers to the final customers. Geoffrion and Powers (1995) later gave a review of the evolution of distribution strategies over the past twenty years, describing how the descendants of the above model can accommodate more echelons and cross commodity detail.

**MIP Optimization Modeling:** Many important supply chain models fall into the MIP (Mixed-Integer Programming) class. This includes most models for vehicle routing and scheduling, facility location and sizing, shipment routing and scheduling, freight consolidation and transportation mode selection. Mixed-integer models are often difficult to optimize, as there can be an exponential number of possible decision alternatives. Some problems are nonlinear MIP. For example, the international plant location problem model presented by Hodder and Dincer (1986) is a large-scale nonlinear MIP, and it is very difficult if not impossible to solve. The model is nonlinear due to the inclusion of financial variables to allocate the costs to plants. By developing an approximation procedure, the authors transform the model into a more tractable, but still nonlinear, formulation. Cohen and Moon (1991) presented a mixed integer, multi-commodity model to find inbound raw material flows, assignment of product lines and specification of production volumes, and outbound finished product flows in a production-distribution network. The model contains binary variables for assigning products to plants, and for determining the part of the concave curve of production costs to be applied. Research results show that global optimal solutions are frequently difficult to obtain unless a special structure exists. A variant of the generalized Benders decomposition technique is applied.

**Stochastic Programming and Robust Optimization Methods:** Stochastic programming deals with a class of optimization models and algorithms in which some of the data may be subject to significant uncertainty. Uncertainty is usually characterized by a probability distribution on the parameters. Such models are appropriate when data evolve over time and decisions need to be made prior to observing the entire data stream.

Swaminathan and Tayur (1999) provided stochastic programming models and effective computational procedures to study inventories of common components, the use of vanilla boxes

for postponement, and the effect of assembly task sequencing on operational performance. They also utilized the inherent structure of problems to develop computationally efficient algorithms based on sub-gradient methods.

In robust optimization, the uncertainty about problem data is treated as deterministic, unknown-but-bounded (e.g., via intervals of confidence for the data). A robust solution is one that tolerates changes in the problem data up to a given bound known as a priori.

Ahmed and Sahinidis (1998) developed a robust optimization framework for the problem of supply chain planning in the process industries. Since the standard stochastic programming formulation of the problem does not address the variability of the uncertain recourse costs across the uncertain parameter scenarios, they extended the stochastic programming formulation to account for robustness of the recourse costs through the use of an appropriate variability criterion. To overcome the difficulty associated with solving the robust models that include non-separable terms, they developed a heuristic procedure for the restricted recourse formulation. This method iteratively enforces recourse robustness while solving the standard stochastic program in each step. Their models can provide the decision maker with a tool to analyze the tradeoff associated with the expected profit and its variability.

**Heuristic Methods:** Heuristic is another important class of methods for generating supply chain alternatives and decisions. A heuristic is simply any intelligent approach that attempts to find good or plausible solutions. Generally, mathematical programming methods are used to solve strategic and higher levels of tactical supply chain planning. This method generally works only for solving linear- and some integer-based models, commonly used in strategic levels of planning. Tactical and operational models are usually not linear and are much too complex to solve using mathematical programming methods. For this reason, heuristic methods are generally used in tactical and operational planning level solvers.

Heuristic methods used in supply chain planning and scheduling include the general random search approaches such as simulated annealing, genetic algorithms and tabu algorithms. Recently, the theory of constraints is also used in supply chain operational planning.

**Simulation based Methods:** This is a method by which a comprehensive supply chain model can be analyzed by considering both its strategic and operational elements. This method can evaluate the effectiveness of a pre-specified policy before developing new ones.

The dynamic nature of supply chains makes the simulation methods necessary for studying the time-varying behavior of supply chains. As suggested by Swaminathan et al. (1998), reengineering the supply chain because of business dynamics is becoming a necessity, but it is not an easy task. Although software simulation tools can ease the burden of analysis, it is still a major endeavor. The use of simulation as a vehicle for understanding issues of organizational decision-making has gained considerable attention and momentum in recent years (Feigin et al. 1996, Kumar et al. 1993, and Malone and Benton 1997). Towill, et al. (1992) used simulation techniques to evaluate effects of various supply chain strategies on demand amplification. Tzafestas and Kapsiotis (1994) utilized a combined analytical/simulation model to analyze supply chains. Swaminathan, et al. (1995) utilized a simulation to study the effect of sharing supplier's available-to-promise information.

### **1.1.5 Demand Response Strategies in Supply Chain Management**

An important ingredient of the supply chain specification is the production planning and control methodology (PPC). Any order for an end product triggers a series of work processes in the supply chain that have to be completed so that the end customer order is satisfied. Generally, the following demand management strategies are employed in supply chain management.

**Engineering-to-Order (ETO):** This strategy places emphasis on the design, which is usually developed after receiving customer requirement and approval by the customer. Consequently, nothing is stocked before the arrival of demand, not even the design.

**Make-to-Stock (MTS):** The end customer orders are filled from the stocks of inventory of finished goods that are kept at the supply chain network's (SCN) various retail points.

**Make-to-Order (MTO):** It is the *confirmed* customer orders that trigger the flow of materials and information in the supply chain. Of the finished goods or component materials,

there is very little or no inventory maintained. Important issues include setting due-dates and release dates for orders flowing in the SCN, scheduling of various orders so as to minimize the variance or mean of order flow times, effective allocation of resources and order tracing mechanisms for efficient customer response.

**Assemble-to-Order (ATO):** Assemble to order involves having the same core assemblies for most products and the ability to vary all other components of the final assembly.

The markets addressed by MTS companies make to stock, based on forecasts, and try to limit risk by limiting the product range. MTO companies are prepared to provide very customized products, but start to produce only after receipt of a firm customer order. ATO companies position themselves in between MTS and MTO, and address primarily the markets of durable products. With an ATO approach, customer order lead times are minimized by dividing the value chain into two stages. (i.e., a stage of module manufacture based on forecasts followed by a stage of final assembly of customized products.) Risk is minimized by modularizing products and by standardizing modules as much as possible.

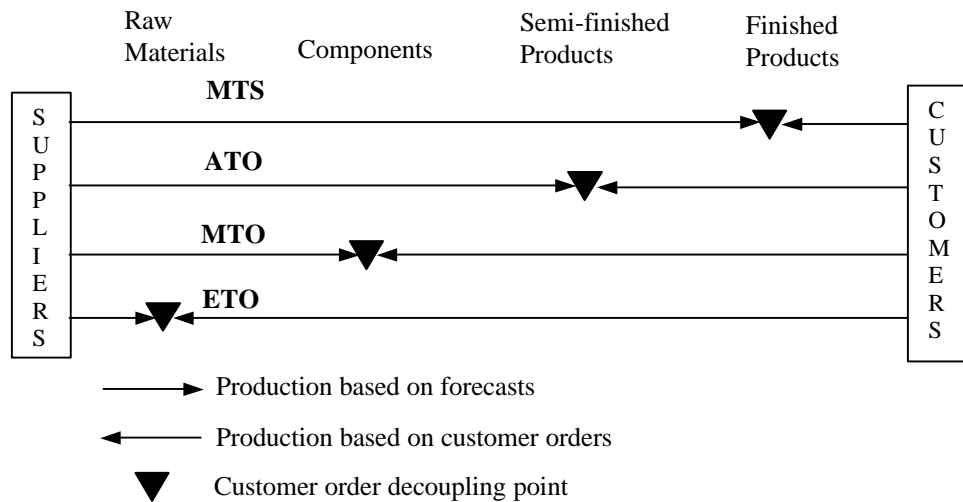


Figure 1.1 Customer order decoupling point (courtesy of Higgins, et al., 1996)

MTS, MTO and ATO companies differ essentially by a different position of the decoupling point. A *decoupling point* is defined as a physical point in the value chain of the production system, which separates the investment stage from the realization stage. Within the

investment stage, operations are executed in response to firm and anticipated demand. Within the realization stage, production is against firm customer orders. The decoupling point determines the minimum customer order lead time. A decoupling point must correspond with stocks somewhere in the supply chain, as the result of the fact that forecasts never are perfect. The position of the decoupling point determines the type of response of a company to its market (Higgins, et al., 1996).

Table 1.1 Comparison between different demand response strategies

Attributes \ Policies	MTS	ATO	MTO	ETO
Delivery time	Short	Medium	Normally long	Normally long
Product range	High	Medium	Low	Very low
Order promising (based on)	Available finished goods	Availability of components and major subassemblies	Capacity for manufacturing engineering	Capacity for manufacturing engineering
Basis for production Planning and scheduling	Forecast	Forecast and backlog	Backlog and orders	Customer orders
Handling of demand Uncertainty	Safety stocks	Over-planning of components and subassemblies	Little uncertainty exists	No control
Primary business Objective	Responsiveness	Customization	Lean production	Lean production

Figure 1.1 shows customer order decoupling points for different demand response strategies. Table 1.1 gives the attribute comparison between different demand management strategies.

### 1.1.6 Product Variety, Postponement and Process Sequencing in Supply Chain

Researchers in the area of operations management define *product variety* as the breadth and the depth of product lines. The end-result of complexity resulting from increased product variety is a proliferation of products, parts, suppliers, and a multiplicity of processes performed within a company. Research in this area can be categorized in two broad classes, strategies for

reducing the level of complexity, and models for reducing the impact of uncertainties by reducing cycle times. Garg and Lee (1999) called them:

- Non-lead time reduction strategies, and
- Lead time reduction strategies.

**Non-lead time reduction strategies:** The main objective of this class of strategies is to reduce the complexity of the system by reducing the number of parts and processes, and by mitigating the effect of uncertainties on total costs in the system. Part commonality, postponement, and process sequencing are some of non-lead time reduction strategies.

**Lead time reduction strategies:** In general, short-term forecasts for an item are more accurate than long-term ones. Lead time reduction is very useful in mitigating the effect of uncertainties because it also reduces the length of the forecasting horizon. Therefore, error between the forecast and the actual realization of demand is much smaller, resulting in lower safety-stock levels. Production line structuring and quick response (QR) are two effective means to reduce the total lead time.

Due to the risk-pooling effect from demands of different end products, the commonality results in lower safety stocks of common components.

The term *postponement* (other terms used to describe this concept include *late customization* and *delayed differentiation*) refers to delaying differentiation of products until as late as is cost-effective (Lee and Tang 1996). Postponement implies both component-level and process-level standardizations, and is a strong way of gaining through economies of scale and scope. Process sequencing is useful in two ways. First, it is a means of effecting postponement. Second, it is a means of reducing the cost during value creation in the supply chain. Basically, benefits due to process sequencing come from *adding the most value to the products as close as possible to the point of realization of their demands*.

Under the postponement strategy, products within a family share common parts and processes until their point of differentiation. At the point of differentiation, a “fan-out” occurs because end products require some special components and/or processes. This naturally leads to

a divergent flow network resembling a distribution network. One way to classify models on postponement is based on:

- The means of effecting postponement (standardization and process sequencing);
- The operating mode (make-to-stock and make-to-order); and
- The supply chain control mechanism (centralized and decentralized control).

For the process sequencing strategy, a method called *operation reversal* is usually used. This approach reverses the order of two operations. As a result, the first operation is common to all products. The basic idea behind *operation reversal* is to defer high value-adding operations (Lee and Tang, 1998).

### **1.1.7 Supply Chain Network Configuration**

#### 1.1.7.1 Definition of Supply Chain Network Configuration

A supply chain can be defined as an integrated business process wherein a number of various business entities (i.e., suppliers, manufacturers, distributors, and retailers) work together. For years, researchers and practitioners have primarily investigated the various processes of the supply chain individually. Recently, however, there has been an increasing attention placed on the performance, design, and analysis of the supply chain as a whole.

Usually, there are two categories of configuration decisions on supply chain networks:

(1) Structural decisions (long term and strategic issues), which include

- Location of factory, warehouse and retailer
- Capacity for each facility
- Transportation modes

(2) Coordination decisions (short term and operational issues), which include

- Inventory deployment: where and how many
- Centralized or decentralized control for replenishment decisions
- Make-to-stock or make-to-order production policy
- Transshipment policies

- Allocation rules for insufficient stocks.

*Supply chain configuration* is concerned with determining supply, production and stock levels in raw materials, subassemblies at different levels of the given bills of material (BoM). End products and information exchange through (possibly) a set of factories, distribution centers of a given production and service network to meet fluctuating demand requirements.

#### 1.1.7.2 Supply Chain Network Configuration Simulation

Simulation technology is emerging as a new tool in supply chain design due to its strength in evaluating system variation and interdependencies. Simulation allows a decision maker to evaluate changes in part of the supply chain and visualize the impact those changes have on the other system components and ultimately the performance of the entire supply chain.

Simulation models can provide a range of results and allow users to improve the statistical accuracy of those results to build a robust and predictive system. In fact, simulation is the only tool that can keep track of all system metrics and predict the interactions between metrics based on changes to system inputs.

The true strength in the simulation of supply chain is the concept of incorporating system variation into the model. Key variants in a supply chain include customer demands, processing yields, raw material and finished goods delivery times, product failure and return rates, and storage capacities. Each of these variables can cause ripples in our supply chain and thus needs to be monitored and checked to understand the interdependencies in the supply chain.

#### 1.1.7.3 Supply Chain Network Configuration Optimization

Through the evaluation of the supply chain network configurations, performance indicators of the supply chain such as fill rate, customer service level, associated cost and response capability can be obtained under different network configurations. Different network configurations include: (1) different stocking levels in raw materials, subassemblies and end products; (2) safety stock location; (3) production policy (make-to-stock or make-to-order); (4)

production capacity (amount and flexibility); (5) allocation rules for limited supplies; and (6) transportation modes.

*Reconfiguration of the supply chain network* from time to time is essential for businesses to retain their competitive edge. *Supply chain configuration optimization* consists of deciding on the safety stock level, reorder point, stocking location, production policy (make-to-stock or make-to-order), production capacity (quantity and flexibility), assignment of distribution resources and transportation modes while imposing standards on the operational units for performance excellence. Therefore, the aim of supply chain configuration optimization is to find the best or the near best alternative configuration with which the supply chain can achieve a high-level performance.

#### 1.1.7.4 Component Commonality in Integrated Supply Chain Networks

Due to the shortened product life cycle and the dynamics of the product market, a company has to improve current products and/or add new products to its existing product line. Different products may share common components (therefore, common inventories) and resources (facilities and capacities). Correspondingly, this requires that the company to reconfigure its supply chain network structure. The configuration of a supply chain network, including the link between entities and operational policies, is changeable and aimed at delivering products to customers in an efficient and effective way. The issue is how to evaluate and then change the structure of the network. The evolution aspect of the supply chain network structure provides the basis for the change.

Product structure (or bill of material) is a key input to an integrated supply chain design. The product structure may have a significant impact on component demand patterns, work-in-process inventory, and fill-rate performance. However, the effect of alternate product structures on integrated supply chains is not well understood.

The development of analytical measures describing product structure characteristics is a prerequisite to understanding the relationships between product structure and supply chain

performance. One characteristic of product structure is the degree of common components in a sub-assembly, a single product or any product family. The traditional MRP methodologies are completely blind to commonality and consequently are unable to exploit it in any way (Miguel, et al., 1999). Fortunately, businesses without commonality are extremely rare. The principal question addressed in this research is: what effect, if any, does the component commonality have on cost, delivery time, fill rate and resource utilization rate?

## **1.2 Problem Statement and Research Objectives**

This dissertation research studies three aspects of an integrated supply chain design:

**Part I:** Process modeling for integrated supply chain design, which includes structured process design, workflow analysis and reengineering of supply chain business processes;

**Part II:** Performance analysis and optimization of production-inventory-distribution supply chain networks under the integrated modeling framework; and

**Part III:** Simulation modeling and statistical analysis for integrated supply chain network configurations.

In the following, problem statement and research objectives for these three parts are given.

### **1.2.1 Process Modeling in Integrated Supply Chain Design**

#### **1.2.1.1 Structured Business Process Modeling of Supply Chain Processes**

Manufacturing has gone through periods of great changes. New information and production technologies have contributed to these changes. The competition today is not among products, but among business models (Turban, et al., 1999). To address these new challenges, computer aided engineering, strategic alliances, management of end-to-end business processes, especially supply chain business processes, are particularly important.

Traditionally, the manufacturing enterprise has been viewed as a sequential arrangement of functions such as design, manufacture, research and development, marketing, finance, etc. The

recent trend has been to view manufacturing as *a collection of value-delivering business processes*. The traditional, functional or hierarchical structure typically presents responsibilities and reporting relationships, whereas the new process structure is a dynamic view of how the organization delivers value to the customer. On one hand, the hierarchical arrangements in the functions require that decisions are to be sought from the top and work processes move up and down the ladder. Lack of proper communications between functions results in work going back and forth with long iteration periods. Usually, the ratio of cycle-time to processing-time is large, most of the cycle time comprising non-value adding times, devoted to move, wait, and information collection. On the other hand, grouping by function enables resources to be pooled among different work activities. In contrast, the business process perspective views a manufacturing enterprise as a collection of business processes that deliver value to customers, and manages them using cross-functional teams in a coordinated manner. Examples of typical processes include: order-to-delivery process, new product development process, shop floor process, and supply chain process.

The supply chain business process encompasses the full range of intra-company and inter-company activities from material procurement, through manufacturing and distribution, to proper delivery of products to customers. Supply chain cost, performance, lead time variability, etc. depend on all constituents of the supply chain. The supply chain management can be defined as the coordination or integration of all activities involved in procuring, producing, delivering and maintaining products/services to customers in various geographical locations. The coordination of logistics functions into integrated supply chain systems has increased the need for improved process quality. Improving the quality of all supply chain processes results in reduced costs, improved resource utilization, and improved process efficiency. Research issues in supply chain processes involve proper production and distribution of multiple products in the order-to-delivery process, choice of alliance partners such as suppliers and distributors in the logistics chain, make-to-order or make-to-stock policies, degree of vertical integration, etc.

Therefore, supply chain process is a process-based or workflow-oriented approach to coordinating all functional units involved in the order-to-delivery process.

#### 1.2.1.2 Workflow Analysis and Reengineering of Supply Chain Processes

Today it is generally accepted that business processes are the basic units of any organization. Hence, managers are confronted with the question: how should the business processes be designed and supported through information technology (IT) so that they are most effective? In the last few years, many researchers and IT suppliers have emphasized that workflow systems should play an important role in the context of business process reengineering and business process management. The benefits mentioned on the vendor side were mainly the following: (1) shorter cycle time — primarily achieved through a reduction of queuing time and through electronic communication; (2) faster and more accurate feedback regarding the state of business cases; and (3) better responsiveness to customers.

Despite the increased interest in the domain of workflow management, the field still lacks precise definitions for some of the concepts. Little agreement exists upon what workflow exactly stands for and which specific features a workflow management system must provide. For an overview of existing definitions and interpretations of workflow and workflow management systems readers can refer to Georgakopoulos et al (1995). In the following the formal definition of workflow presented by the Workflow Management Coalition — WfMC (Hollingsworth 1994) will be used:

*Workflow is the automation of a business process, in whole or part, during which documents, information or tasks are passed from one participant to another for action, according to a set of procedural rules.*

Automatic analysis techniques for business processes are crucial for today's workflow applications. Since business processes are rapidly changing (sometimes even at runtime), only automatic techniques can detect processes that might cause deadlocks or congestion.

According to the WfMC, a workflow system can be described as “a system that defines, creates and manages the execution of workflows through the use of software, running on one or more workflow engines, which is able to interpret the process definition, interact with workflow participants and, where required, invoke the use of IT tools and applications” (WfMC 1999). Therefore, a workflow system comprises a workflow engine (sometimes referred to as workflow management system) plus one or several applications based on the workflow engine. In other words, WfMS are regarded as tools for the efficient execution of business processes, which also allow the continuous evolution of processes.

As a result of developments in both management science (e.g., business process reengineering — BPR) and information systems (e.g., Workflow Management/WFM and ERP systems), enterprise information systems are changing from data-oriented to process-oriented. A business process operating system is needed for managing, controlling and coordinating business processes. Workflow management systems are such systems. The goal of workflow management system is to manage the flow of work such that the work is done at the right time by the proper resource. There exist three types of flows in processes: information flow, service flow and material flow. These flows in process models can be generally called workflows.

The correctness, effectiveness, and efficiency of the business processes supported by WFM/ERP systems are vital to the organization. A workflow process definition, which contains errors, may lead to losing customers, damage claims, and loss of goodwill. Flaws in the design of a workflow definition may also lead to high throughput times, low service levels, and a need for excess capacity. This is why it is important to analyze a workflow process definition before it is put into production.

Due to the highly complex nature of large supply chains, designing, analyzing and re-engineering of supply chain processes using formal and quantitative approaches are very difficult. Several leading researchers, such as Berry and et al (1995), Evans and et al (1995), van der Aalst (1997, 1998), Lin and Shaw (1998) and Vernadat (1996), have developed some frameworks and models to design and analyze the supply chain processes. These existing

models, however, are either oversimplified or just qualitatively described (some of them are just based on simulation study), and are difficult to be applied for evaluating real supply chains with quantitative analysis and decisions. Furthermore, few studies focused on integrated modeling and analysis that can be used to determine the supply chain throughput capacity incorporating multiple stages. Literature surveys done by the author indicates that there is currently no formal and quantitative model that is capable of capturing some important issues including the verification and validation of overall supply chain business processes and the effect of operation sequences on supply chain process performance and cost. An integrated formal and quantitative model, addressing the above mentioned issues that allow supply chain managers to quickly evaluate various design and operation alternatives with satisfactory accuracy, becomes imperative.

#### 1.2.1.3 Objective and Significance of the Research

Traditional analysis has assumed that the enterprise is weakly coupled, i.e., various subsystems work almost independently. Process-oriented approach addresses the issue of integrated modeling and analysis. It is becoming more appropriate since today's manufacturing enterprises are becoming more strongly coupled in terms of material, information and service flows. Past studies all neglected significant impacts of this integration issue because of dramatic increase in modeling complexity required. Models resulted from past studies are therefore very limited in their capability and applicability to analyze real supply chain business processes.

In workflow systems, there are no stocks, transport is timeless, and all tasks are executed for a single case. This indicates that in many situations (but not always) the typical physical constraints do not apply. Nevertheless, deadlocks, dangling tasks, etc. are still possible. Therefore, verification and validation analysis is needed. Moreover, the execution of tasks (activities) takes time and resources are limited. Therefore, performance analysis is also useful.

The objective of this research is to develop an integrated and quantitative modeling framework and analysis methodology for supply chain business processes. The model-based

analysis of alternative supply chain structures and operating policies for manufacturing businesses is presented. Through such process design and analysis studies, strategic directions for improvement can be identified, and decision support tools for operating an integrated supply chain can be developed.

As process-oriented supply chain design, analysis and re-engineering is a new field, empirical research in this particular area is still slight. This calls for the use of a grounded theory research approach. Petri nets are frequently used for modeling both information systems and business processes. Petri nets are considered capable because of their following features:

- (1) Graphical description yielding in a workflow representation that can be understood by various groups of people.
- (2) Formal basis: workflow models based on Petri nets can be formally analyzed in order to achieve improvements of the modeled processes.
- (3) Enactable models: Petri net based workflow models can be enacted.

Therefore, in this research, a Petri net-based framework is proposed. Petri nets combine a strong mathematical foundation with an intuitive graphical representation. The formal basis can be used to compare the expressive power of existing systems, prove properties, formalize new concepts, and analyze workflow processes.

In particular, the proposed research work has two goals: (1) supply chain process design: to formally establish a series of generic building blocks and a modeling algorithm from which structured process models can be built; and (2) supply chain workflow analysis: to make workflow verification analysis (i.e., establishing the correctness of a workflow) and validation analysis (i.e., testing whether the workflow behaves as expected) using Petri nets.

## **1.2.2 Performance Analysis of Integrated Supply Chain Networks**

### **1.2.2.1 Overview and Problem Statement**

A central problem in integrated supply chain network design is to quantify and optimize the trade-off between customer service levels and the inventory investment required to support

those service requirements. The problem becomes more challenging because of the dynamic nature of the supply chains: prolific product variety, short lifetime products, frequent new product introduction, non-stationary customer demand, and frequently changing service-level requirements. This dynamic nature of complex supply chains causes that the trade-off between customer service levels and the inventory investment changes over time. In turn, the performance of supply chains must be continually reevaluated and the inventory-service level trade-off has to be optimized continuously. Therefore, an analytic model to be used for both performance analysis and inventory-service trade-off optimization is in need. Furthermore, to answer “what-if” questions quickly, such an analytic model has to be computed efficiently.

In summary, the following needs are identified for performance evaluation of an integrated supply chain network: (1) an integrated modeling framework; (2) ways of dealing with uncertainties in supply, demand, and internal processes; (3) means of capturing the interdependencies between different components; and (4) simplicity and tractability for computation.

#### 1.2.2.2 Research Objectives

This research is geared toward providing and developing effective solutions for performance analysis of integrated supply chain networks. In view of the above, the following objectives are pursued:

(1) To provide an analytical modeling framework for integrated supply chain networks, in which the interdependencies between model components are captured;

(2) To develop a network of inventory-queue models for performance analysis of an integrated supply network with inventory control at all sites; and

(3) To extend the previous work developed for supply network model with base-stock control and service requirements. Instead of one-for-one base stock policy, batch-ordering policy and lot-sizing problems are considered. The assumption of uncapacitated production is

often not true in practice, therefore,  $GI^x/G/1$  queueing analysis is used to replace the  $M^x/G/\infty$  queue based method.

### **1.2.3 Simulation Modeling and Analysis for Integrated Supply Chain Network**

#### **Configurations**

##### **1.2.3.1 Problem Statement for Multi-Echelon Supply Networks with Stochastic Demand**

Multi-echelon models can be described as methods for coordination of the local decentralized inventory control systems. Inventory control in multi-echelon systems is the core of integrated supply chain design and a very promising application area. Multi-echelon inventory control is also a very challenging research area.

The fundamental problem in two-level inventory systems is to find the best balance between the central stock at the warehouse and the local stock at the retailers. The inventories at different levels will support each other. The optimal solution of a multi-echelon inventory problem will depend on system structure, demand distributions, lead times, and cost etc. The replenishment lead times at retailers are evidently not independent since they depend on the inventory situation at the warehouse.

In general, it is more difficult to evaluate the general batch ordering policies. The main source of the difficulties is the fact that a retailer's demand will no longer immediately trigger a corresponding retailer order. Assume that the retailer's demand is Poisson and retailer  $i$  orders in batches of size  $Q_i$  from the manufacturer. This means that every  $Q_i$ th demand at the retailer will trigger an order, and the demand from the retailer at the warehouse is therefore an Erlang renewal process with  $Q_i$  stages. Consequently, the demand process at the warehouse is a superposition of  $N$  such Erlang processes instead of the simple Poisson process in the case of one-for-one ordering where  $N$  is the number of the retailers. It is usually practical to use various approximations when evaluating the costs. Several different types of approximations have been suggested in the literature.

The problem on integrated supply chain network configurations becomes more challenging since not only the distribution function but also the manufacturing function will be considered. In addition, there are many variables involved in the network configurations. More important, there exist interactions between some variables.

There are a few strategies available for a supply chain to simultaneously deal with product variety and keep high levels of productivity. Some of these are supply chain integration, common components, and process flexibility. In the field of component commonality, the majority of work published so far has concentrated on the related effects on the inventories only.

Problems with the integrated characteristics given above are difficult to be transformed into mathematical optimization models. When possible, often there are tens of thousands of constraints and variables for a deterministic situation. However, traditional deterministic optimization is not suitable for capturing the truly dynamic behavior of most real-world applications. The main reason is that such applications involve data uncertainties that arise because information that will be needed in subsequent decision stages is not available to the decision maker when the decision must be made (Beamon, 1998). And very often, the problem statement by mathematical modeling is simplified to allow for analytical solutions. Although these analysis methods help us gain insight in the problem, they can only be applied in some specific situations. On the other hand, simulation is a very powerful analysis technique, since it does not set additional restraints.

#### 1.2.3.2 Importance of the Research

Poorly integrated enterprise logistic system components and processes make it more difficult for firms to compete and differentiate themselves. Only with an integrated approach to supply network configuration analysis and management can firms locate and remove sources of inefficiency and waste (Ross, Venkataramanan and Ernstberger, 1998).

Through the performance evaluation, the impacts of different factors such as reorder point, safety stock, and degree of component commonality can be investigated. Thus, simulation

study can help us gain insight in network configuration problem. In turn, this can assist companies' decision-making in their supply chain management.

#### 1.2.3.3 Research Objectives

The primary objective of this research is to explore channel and supplier dynamics, evaluate alternative control policies, and identify key factors that are crucial to the total supply chain performance. We utilize and extend techniques in modeling, simulation, and statistical analysis.

In particular, the research objectives are:

- (1) To evaluate the impacts of different inventory reorder policies for multi-echelon distribution systems;
- (2) To compare the performance of the proposed transshipment policy with that of the traditional policy in multi-echelon distribution systems;
- (3) To conduct the statistical analysis on the effects of component commonality on integrated supply chain performance; and
- (4) To provide a modeling methodology for integrated supply network configurations by using resource and state based modular building blocks.

### **1.3 Research Approach**

To achieve the development of the new design methodology for integrated supply chain networks, this research approach consists of the following phases and steps.

Phase I:

Step 1. Structured supply chain business processes are addressed in this step. In this regard, CIMOSA (Computer Integrated Manufacturing Open System Architecture) process patterns and free-choice Petri nets are used to design structured supply chain processes.

Step 2. Supply chain workflow analysis and process reengineering are our focuses in Step 2. For this study, information flow and service flow (or transaction flow) are concerned. The basic methodology includes object-oriented Petri-net modeling approach, P-invariant based verification, and net-unfolding-based sequencing analysis.

Information technology application in the supply chain design is emphasized in Phase I.

Phase II:

Step 1. An integrated framework for modeling and performance analysis of supply chain networks is presented.

Step 2. Queueing theory is employed to analyze different performance measures of supply chain networks in this step. Production authorization (PA) cards control mechanism is adopted to facilitate the analytic performance analysis for supply chain networks.

Step 3. The supply chain optimization issue is presented. To find out the best trade-off between customer service levels and the inventory investment, nonlinear programming techniques are used.

In Phase II, applications of operations research techniques in integrated supply chain network design are explored.

Phase III:

Step 1. A resource and state based modular modeling methodology is presented to build the simulation model for integrated supply chain networks.

Step 2. Our effort is made to compare the performance measures of multi-echelon distribution systems controlled by installation stock policy and echelon stock policy.

Step 3. By adding the flexibility of lateral transshipments between retailers, the performance of the proposed *alternate transshipment policy* is evaluated and compared with that of the traditional *random transshipment policy*.

Step 4. Analysis-of-variance and Tukey's test are employed to study the effects of component commonality on integrated supply chain network performance.

Phase III emphasizes the application of simulation techniques in integrated supply chain network design.

#### **1.4 Contributions of the Research**

This research makes a first attempt to integrate process modeling, analytical performance optimization, and configuration simulation into an integrated framework that allows quantitative analysis of supply chain networks. The most representative topics in integrated supply chain network design are addressed. These problems are: (1) process modeling and analysis of supply chain workflow systems; (2) performance analysis and optimization of multi-stage production-inventory-distribution networks; and (3) simulation modeling and statistical analysis of integrated supply chain network configurations. Meaningful results and useful insights are provided for these problems. As a direct consequence, the implementation of the research results will achieve substantial business benefits.

In particular, the proposed research makes the following contributions to the literature for the supply chain workflow modeling and analysis problem:

- (1) An effective structured process modeling algorithm to design a structured supply chain business process by using well-behaved supply chain process constructs.
- (2) A modular modeling approach based on object-oriented Petri nets to facilitate the modeling of supply chain workflows.
- (3) A P-invariant based procedure to make the verification analysis for supply chain workflow processes.
- (4) A sequencing analysis method based on Petri-net-unfolding techniques used for supply chain workflow processes.

For the performance analysis and optimization of multi-stage production-inventory-distribution networks, the contributions of this research are as follows:

- (1) An integrated modeling framework for multi-stage supply chain networks, in which the interdependencies between model components are captured.

- (2) A network of inventory-queue models for performance analysis of an integrated supply network with inventory control at all sites.
- (3) Extension of the previous work to consider batch-ordering policy, lot-sizing and capacitated production.
- (4)  $GI^x/G/1$  queue based closed-form formulae for expected values of on-hand inventory and backorders, fill rates and stock-out probabilities of stores.
- (5) An optimization model to minimize the total expected inventory capital throughout the network while satisfying customer service-level requirements.

The following contributions are made by the simulation study of integrated supply chain network configurations:

- (1) A resource and state based simulation modeling and analysis approach for decision-making in integrated supply chain network configurations and reconfigurations.
- (2) A comparison of the effects of different control policies on the performance of multi-echelon distribution networks. These control policies are:
  - *Installation* stock reorder point policy
  - *Echelon* stock reorder point policy
  - *Random* transshipment policy
  - *Alternate* transshipment policy
- (3) Analysis-of-variance and Tukey's test on the effects of the degree of component commonality on different supply chain performance measures such as delivery time, fill rate and cost in an integrated environment.

## **1.5 Organization of the Dissertation**

This research proposal is organized as follows. Chapter 2 provides a detailed and exhaustive literature review on integrated supply chain design. This is divided into three relevant aspects, i.e., process modeling and analysis of supply chain workflows, performance evaluation

and optimization of production-inventory-distribution networks, and simulation modeling and analysis for integrated supply chain network configurations. In Chapter 3, a structured process modeling algorithm for supply chain business processes using CIMOSA (Computer Integrated Manufacturing Open System Architecture) behavioral rules and free-choice Petri nets is presented. Through this algorithm, the logic properties of supply chain processes such as liveness and boundedness can be verified in polynomial time. Chapter 4 introduces an object-oriented Petri net modeling approach and net-unfolding-based sequencing analysis for supply chain workflows. Chapter 5 is devoted to present the network topology and basic elements of the multi-stage production-inventory-distribution supply chain networks. The multi-stage supply chain network performance analysis using queueing theory, and optimization study on the trade-off between inventory cost and service level are given in Chapter 6. Simulation modeling and statistical analysis of integrated supply chain network configurations is the concern of Chapter 7. In this chapter, a comparison of the effects of different control policies on the performance of multi-echelon distribution networks is given. Chapter 7 also investigates the effects of the component commonality on different supply chain performance measures such as delivery time, fill rate and cost in an integrated environment. As the last chapter, Chapter 8 summarizes this research and concludes with a discussion on some possible research extensions.

## Chapter 2

### Literature Review

#### 2.1 Literature Review on Supply Chain Business Processes and Workflows

##### 2.1.1 Design of Supply Chain Processes

Varying market demands require frequent operational and organizational changes in the enterprise supply chain processes. In response to such a challenge, the enterprises have to impose adaptations in the relevant areas of supply chain business processes. Before redesigned business processes are implemented, process models should be employed to verify and correct potential problems. Through verification, some anomalies such as deadlock, endless loops and dangling activities can be avoided. Process models without these anomalies are called well-behaved ones.

The basic elements of a process model are:

- (1) *Structure* of the business processes: a business process is a set of tasks that have to be completed in some kind of order (possibly differing for each new job); the possible routes throughout the process, leading to the execution of individual tasks, are essential for determining the process throughput time.
- (2) *Resource schedule*: it is the way how resources are distributed over the different tasks within the process; both the available type of resources and the number of resources may determine the flow of jobs through specific points in the process.
- (3) *Service characteristics* of the resources active within the process: differences in service productivity per resource influence the process throughput time.
- (4) *Arrival rate* of new jobs: the balance between new arrivals and available resources determines whether waiting time arises.

The popularity of different process management approaches like lean management (Womack et al 1991), activity-based costing (Tunney and Reeve 1992), total quality management (Ishikawa 1985 and Oakland 1993), business process reengineering (Hammer 1990,

Hammer and Champy 1993), process innovation (Davenport and Short 1990, Davenport 1992), workflow management (Georgakopoulos et al 1995), and supply chain management (Poirier 1999) have two main effects concerning the requirements on process models. First, the number and variety of model designers and users have spread enormously. As a consequence, the understandability of process models is of growing importance. Secondly, the number and variety of purposes for which the process models are used are growing.

A business process can be described as a set of *activities* that are being executed according to certain *rules* with respect to certain *objectives*. The *execution* of a business process describes the execution of the corresponding activities such that the rules are obeyed and the objectives are met. The execution of a business process usually involves decisions on alternative routings, i.e., choices between the executions of alternative activities have to be made.

During the execution of a business process, activities have to be coordinated. *Resources* have to be provided where needed for the execution of activities. A *business process specification* describes which activities have to be executed in what order (including concurrent execution) and what resources are needed for the execution of these activities.

Process modeling is supposed to be an instrument for coping with the complexity of process planning and control. Especially in enterprise-wide process management projects the design of integrated process models can become a comprehensive challenge. The number of process models can easily be higher 500 with five or more different levels.

In this research, the CIMOSA (Computer Integrated Manufacturing Open System Architecture) is used to provide a framework for users in modeling business process structures, deriving enterprise system design and implementation (ESPRIT Consortium 1993 and Zelm et al 1995). The generic building blocks from CIMOSA modeling language can be used to describe the semantics of an enterprise business process. The CIMOSA modeling approach includes and extends previous function (activity) modeling approaches already in use in industry. The most significant extension is the modeling of the process behavior.

Process models should include a specification of activities, resources assigned to the activities, business rules, exception handling and temporal aspects (Oberweis 1996). There are four trends associated with business processes: (1) they are becoming more important such as for BPR; (2) they are subject to frequent changes; (3) they are becoming more complex; and (4) they are increasing in number. These features make the verification of process models a very difficult task. Therefore, structured process modeling languages, algorithms and analysis techniques are needed. However, for most current process modeling tools such as flowchart and state transition diagram, the verification of process models is very difficult, if not impossible. Petri net modeling is a very popular and powerful method for modeling and analysis of systems that exhibit concurrency, parallelism, synchronization, non-determinism and resource sharing features (Aguiar et al 1993, Descrocher et al 1995, Molly 1982, Murata 1989, Narahari et al 1985, Reisig 1985 and Zhou et al 1989). For a general review of Petri nets, the reader is referred to Murata (1989). For arbitrary Petri nets, the checking of well-behaved properties is a NP-hard problem. In this research, free-choice Petri nets are employed to check the well-behaved properties of process models. The reason for choosing free-choice Petri nets is that it is a good compromise between expressive power and analyzability. Some key Petri nets related definitions and notations are given in the Appendix A.

### **2.1.2 Verification Analysis of Supply Chain Workflows**

Within the last years workflow management has become a technology that is being more and more used in order to support business processes. Business processes supported by WFM are *case-driven*, i.e., tasks are executed for specific cases. Receiving customer orders, accepting orders, raw material supply flow from suppliers, inventory level information flow, production flow for orders, billing, delivery flow, transportation flow, and customer service level information flow are typical case-driven processes and workflows in supply chain business processes. These case-driven processes are marked by three dimensions: (1) the control-flow dimension, (2) the resource dimension, and (3) the case dimension.

One of the major challenges in the context of a workflow analysis is the correctness of workflow specification. The more challenging features are reachability and executability of workflow steps. This means that one workflow can be executed at all, i.e., the execution path can reach this workflow step eventually.

To verify and correct potential problems, business process models should be built and employed. Through the verification analysis, some anomalies such as deadlock and congestion can be avoided. To efficiently and optimally implement the processes, a sequencing analysis for activities is necessary. The principal idea of process-oriented design, modeling and analysis is to explicitly grasp all process-related information including activities, resources and organizational units as well as their interdependencies, and to describe them in a model.

Enterprises can only become a full player in the global market place by reshaping corporate structures around business processes and by making their internal processes align with and support integrated value-chains. Therefore, reengineering of supply chain operations has to be made more frequently than before. This also requires that new business models are created on the basis of common *business objects* which provide a powerful mechanism for realizing and implementing business models.

Most studies on the Petri net application in process modeling focus on either information aspect or function aspect, and modeling flexibility and modular analysis are not always considered in their approaches. Thus, a modular design, modeling and analysis approach that integrates function, information, resource and organization is critical to support complex, dynamic and distributed supply chain processes.

## **2.2 Literature Review on Multi-Stage Production-Inventory-Distribution Supply Chain Networks**

Axsater (1993) provides a good review of models and algorithms for the analysis of continuous review policies in multi-echelon inventory networks. The classic model of a continuous review, multi-echelon inventory system is METRIC (Sherbrooke 1968), developed

for the U.S. Air Force as a planning tool for controlling inventory of repairable items. The model consists of two echelons. The lower one consists of  $n$  identical bases or stocking locations, and the upper one consists of a single depot or warehouse that supplies the bases with repaired parts. The original model considers a single item, i.i.d. lead times, one-for-one replenishment policy, no capacity constraints, and a stationary compound Poisson demand process. The objective of the model is to identify stocking policies at the bases and the depot to minimize backorders at the base level subject to a constraint on the inventory investment. Subsequent work has extended the original model in various ways. MOD-METRIC (Muckstadt 1973) extends the model to handle multiple items and multi-indenture. Sherbrooke (1986, VARI-METRIC) and Graves (1985) propose methods for improving the model's accuracy. Lee and Moinzadeh (1987a, 1987b) allow for batch ordering and shipping. Deuermeyer and Schwartz (1981) and Svoronos and Zipkin (1988) develop simplified approaches based on decomposition. Svoronos and Zipkin (1991) consider a model with non-overtaking repair (or transit) times as opposed to the i.i.d. assumption used elsewhere.

Clark and Scarf (1960), Federgruen and Zipkin (1984), and Rosling (1989) adopt *centralized control mechanism*. Total costs of a system operating under centralized control are usually lower than those of a decentralized system (Axsater and Rosling 1993). However, centralized policies can be very complicated for most general systems. And in practice, most supply chains still operate in a decentralized mode. Graves (1988), Cohen and Lee (1988), and Lee and Billington (1993), have employed the *decentralized control policy* in supply chain networks.

Graves (1988) adopts decentralized control mechanism to model production networks. A periodic-review, base-stock inventory policy is used and demands are assumed to be stationary and normally distributed. The key to the proposed solution approach is aggregating the results of single-site inventory models in order to evaluate the performance of the network. Although this model can be used to perform different types of supply chain analyses, assuming total flexibility in varying production rates at each site is a limitation of this model.

Cohen and Lee (1988) model a more general decentralized network in which the manufacturing site has multiple inputs, and its outputs feed a divergent distribution network. Cohen and Lee decompose the network into several sub-models: material control, production, and distribution. The material control sub-model is an assembly system that supplies material to the manufacturing sites. Outputs from manufacturing sites are fed into a divergent flow distribution sub-model. The key linkage between manufacturing and distribution is the manufacturing lead time that becomes the replenishment lead time for the distribution sub-model. In this general decentralized network, the distribution sub-model uses an  $(s, S)$  policy at each site, while the manufacturing sub-model operates under an  $(nQ, R)$  inventory policy. Authors also assume end-product demands to follow a stationary Poisson process. A limitation of the proposed model is that only a single manufacturing site is allowed in the network.

Lee and Billington (1993), henceforth referred to as LB, develop an analytical model for a decentralized supply chain. Their model assumes each site operates under a periodic-review, base-stock inventory policy and the demands for end-products are normally distributed. A key assumption in the model is that the replenishment lead time for a product at a node comprises the material lead time, the production lead time, and the delay time. Like Graves (1988), LB also evaluates performance of the network by aggregating the solutions of multiple single-product, single-site inventory problems. One of the advantages of this framework is the ability to analyze the first two moments of all the performance metrics.

Garg (1999) develops a decentralized supply chain modeling and analysis tool (SCMAT) on designing products and processes for supply chain management at a large electronics manufacturer (LEM). SCMAT contains two sub-models: queueing network sub-model which is used to attain the production lead time for a site and inventory network sub-model which is used to calculate the base-stock level for each SKU flowing through every site. The output (production lead time) of the queueing network sub-model is one input of the inventory network sub-model. Given the base-stock level and the values of its three drivers (demand, replenishment lead time, and the service-level or the fill-rate requirement), one can compute various

performance measures useful for obtaining managerial insight. These performance measures include the mean and variance of the on-hand inventory, the mean and variance of the backorder level, the mean and variance of the response time, and the capacity utilization at each node in the network.

SCMAT extends previous work by incorporating queueing approximations to model the congestion effects at each site. Like the previous models, SCMAT makes several approximations in order to keep the model analytically tractable. Like Graves and LB, Garg (1999) also assumes end product demands to be stationary and normally distributed. Unlike LB model, which was not applicable at LEM because of non-availability of several types of input data. For example, the LB model requires the user to input delay at the downstream production site due to non-availability of parts. Another input the LB model requires is the capacity at a node allocated to each product flowing through that node. This input effectively allows one to decompose the node into sub-nodes, one for each product. One can then evaluate the performance of the entire network by using the results of a single-site inventory model for each product-node combination. In practice, however, many products usually share common resources: manufacturing lines, storage space, etc. It is very difficult to pre-determine the capacity allocated to each product flowing through a node. In practice, managers at the LEM are also interested in capacity requirements at each site in the supply chain and in studying the implications of capacity on lead times and inventories. This type of analysis cannot be done using periodic-review models of inventory networks. In Garg (1999), SCMAT explicitly incorporates the *congestion effects due to capacity limitations at each node, and the interference effect because of multi-product flows through each node*. While the models developed by Graves (1988), Cohen and Lee (1988), and LB, do not consider these effects. Queueing models allow one to capture the above-mentioned effects explicitly. SCMAT model incorporates queueing approximations within the inventory modeling framework.

The recent work of Ettl et al. (2000) aims at modeling large-scale, end-to-end enterprise supply chains, such as those in the PC industry. They develop a supply chain network model that

takes as input the bill-of-materials, the nominal lead times, the demand and cost data, and the required customer service levels. In return, the model generates the base-stock level at each store — the stocking location for a component or an end-product. They assume a distributed inventory control mechanism whereby each site in the network operates according to a base-stock control policy. This is a continuous review, one-for-one replenishment policy, also known as an (S-1, S) policy. This base-stock policy makes authors avoid the consideration on determining the lot sizes at each store. They further assume that, given there are no stock-outs at upstream stores, the replenishment lead time of any store is independent of the number of outstanding orders. In this sense, stores are uncapacitated. Ettl et al. (2000) formulate the model in terms of base-stock levels. For performance evaluation, base-stock levels are treated as input and output includes customer service levels, fill rates and inventory levels throughout the network. To perform optimization, they formulate a constrained nonlinear optimization model, which minimizes the total average dollar value of inventory in the network, subject to meeting the service-level requirements of end customers. The optimization is carried out using the conjugate gradient method, where they make use of gradient estimates obtained analytically.

The key ingredient of the models in (Ettl et al. 2000) is the analysis of the actual lead times at each store and the associated demand over such lead times, along with a characterization of the operation at each store via an inventory-queue model. To handle the dynamic nature of supply chains and in particular the non-stationary feature of demand, a rolling-horizon point of view (it is quite popular in materials requirement planning and distribution resource planning tools) is adopted. That is, as time evolves and new information becomes available, the decision variables and the performance measures change as well.

Like the LB model, Ettl et al. (2000) also use normal approximation to characterize the demand over lead times and to compute related performance measures. Unlike the LB model, Ettl et al. (2000) characterize the lead times based on queueing analysis and consider the optimization problem. Instead of assuming stationary demand in LB model, Ettl et al. (2000) treat non-stationary demand via the rolling-horizon approach.

In summary, the centerpiece of Ettl et al. (2000) is a network of inventory queues, which integrates inventory control with the delay-capacity features of queues. The network configuration is determined by the BOM structure of the end products. The solution approach is a decomposition-based approximation, coupled with nonlinear optimization using conjugate gradient search. The model can be used not only to study the inventory-service tradeoff, but also to compare the effects on inventory and service performances through changing the network configurations, i.e., the supply chain structure, and to identify the best configuration.

## **2.3 Literature Review on Simulation of Integrated Supply Network Configurations**

### **2.3.1 Simulation in Supply Chain Management**

Supply chain performance can be improved by reducing the uncertainties. It is clear that there is a need for some level of coordination of activities and processes within and between organizations in the supply chain to reduce uncertainties and add more value for customers. This requires that the interdependence relations between decision variables of different processes, stages and organizations to be established. These relations may change with time and are very difficult to analytically modeled, if not impossible. However, the simulation provides a much more flexible means to model the dynamic and complex networks. Simulation is considered the most reliable method to date in studying the dynamic performance of supply chain networks. Simulation also provides an effective tool to evaluate supply chain reengineering efforts in terms of performance and risk.

Towill (1991) and Towill et al. (1992) use simulation techniques to evaluate the effects of various supply chain strategies on demand amplification. The strategies investigated are as follows (Towill et al. 1992):

1. Eliminating the distribution echelon of the supply chain, by including the distribution function in the manufacturing echelon.
2. Integrating the flow of information throughout the chain.
3. Implementing a just-in-time (JIT) inventory policy to reduce time delays.

4. Improving the movement of intermediate products and materials by modifying the order quantity procedures.
5. Modifying the parameters of the existing order quantity procedures.

The objective of the simulation model is to determine which strategies are the most effective in smoothing the variations in the demand pattern. The just-in-time strategy (strategy 3 above) and the echelon removal strategy (strategy 1 above) were observed to be the most effective in smoothing demand variations.

Bhaskaran (1998) illustrates the magnitude of a supply chain reengineering project for a blanking and stamping operation at General Motors, using simulation as the primary analytical tool. The paper describes the level of detail required to understand material and information flows and evaluates different system configurations to identify improvement. However, supply chain interactions typically involve more sophisticated control mechanisms. For example, when an important order comes in, it may have to be processed first, ahead of other orders. Also, processing of an item may involve more than just waiting at the service center for some time. For example, when an order is processed, components may have to be assembled and that could, in turn, trigger some events based on their inventory position. Decision rules may have to be used at various points when events are processed.

Although the advantages of simulation models, there are two major problems associated with building customized simulation models: (1) they take a long time to develop and, (2) they are very specific and have limited reuse. Swaminathan, Smith and Sadeh (1998) provide a supply chain modeling framework, which enables rapid development of customized decision support tools for SCM, for rapidly reconfiguring the supply chain based upon studies of several different supply chains. The authors' approach uses library-based supply chain modeling components. They utilize a multi-agent paradigm for modeling and analysis of supply chain. Multi-agent computational environments are suitable for studying a broad class of coordination issues involving multiple autonomous or semiautonomous problem-solving agents. Swaminathan, Smith and Sadeh (1998) identify different agents in the supply chain and provide each agent with

an ability to utilize a subset of control elements. The control elements help in decision making at the agent level by utilizing various policies (derived from analytical models such as inventory policies, just-in-time release, and routing algorithms) for demand, supply, information, and materials control within the supply chain. Their analysis is based on discrete-event simulation of the various alternatives and control policies. Combination of analytical and simulation models makes the framework attractive to study both the static and dynamic aspects of problems.

### **2.3.2 Lateral Transshipment in Multi-Echelon Distribution Systems**

The earliest contribution to the emergency lateral transshipment problem is due to Krishnan and Rao (1965), who derives the optimal order-up-to quantities assuming that the replenishment lead time is zero and all costs at each location are identical. Tagaras (1989) extends the two-location version of Krishnan and Rao's model by allowing different costs at the two locations and by adding service level constraints. Robinson (1990) examines the general case of multiple locations with different cost parameters, maintaining the assumptions of instantaneous replenishment and transshipment, and proves the optimality of the base stock ordering policy. However, the optimal order-up-to points can be found analytically only when the cost parameters are equal at every outlet or when there are only two outlets. For the general case Robinson (1990) proposes a heuristic solution technique employing Monte Carlo integration.

Tagaras' paper (1999) extends the previous work of Tagaras and Cohen (1992) to inventory systems with more than two identical cost retailers forming a complete pooling group. The paper also provides results that have important implications for the design of distribution systems.

### **2.3.3 Component Commonality in Supply Chain Networks**

There exist a rich literature studying component commonality. However, the majority of work published so far has concentrated on the related effects of inventory and safety stock levels only. It has been clearly demonstrated in the literature that introducing a common component

that replaces a number of unique components reduces the level of safety stock required to meet service level requirements.

Collier (1981) initiates an interest in taking advantage of the commonality situation. He finds that increased commonality reduces production costs through larger production lot sizes and reduces operation costs through increased standardization.

Eynan and Rosenblatt (1996) study the effects of increasing component commonality for a single-period model. They develop optimal solutions for the commonality and non-commonality models and provide bounds on the total savings resulting from using commonality. They demonstrate, under general and specific component cost structures, that some forms of commonality may not always be a preferred strategy. Furthermore, they present conditions under which commonality should not be used.

Hillier (1999) develop a simple multiple-period model with service level constraints to compare the effects of commonality in the single-period and multiple-period case. The results are drastically different for these two cases. When the common component is more expensive than the components it replaces, commonality is often still beneficial in the single-period model, but almost never in the multiple-period model.

Hong and Hayya's paper (1998) consider the effects of component commonality in a single-stage manufacturing system of two products manufactured in a single facility. They consider two economic lot schedules: the common cycle (CC) and basic period (BP) schedules. For each lot schedule, an expression for the total relevant cost for the system was given in their paper.

In an environment where demands are stochastic, it seems a good strategy to store inventory in the form of semi-finished products (vanilla boxes) that can serve more than one final product. However, finding the optimal configurations and inventory levels of the vanilla boxes could be a challenging task. Swaminathan and Tayur (1998) model the above problem as a two-stage integer program with recourse. By utilizing structural decomposition of the problem and sub-gradient derivative methods, they provide an effective solution procedure.