
Masters Theses

Student Theses and Dissertations

Spring 2008

Quantifying the desired degree of supply chain flexibility

Poorna Marappa

Follow this and additional works at: https://scholarsmine.mst.edu/masters_theses



Part of the [Systems Engineering Commons](#)

Department:

Recommended Citation

Marappa, Poorna, "Quantifying the desired degree of supply chain flexibility" (2008). *Masters Theses*. 5018.

https://scholarsmine.mst.edu/masters_theses/5018

This thesis is brought to you by Scholars' Mine, a service of the Missouri S&T Library and Learning Resources. This work is protected by U. S. Copyright Law. Unauthorized use including reproduction for redistribution requires the permission of the copyright holder. For more information, please contact scholarsmine@mst.edu.

**QUANTIFYING THE DESIRED DEGREE OF SUPPLY CHAIN
FLEXIBILITY**

by

POORNA MARAPPA

A THESIS

Presented to the Graduate Faculty of the

MISSOURI UNIVERSITY OF SCIENCE AND TECHNOLOGY

In Partial Fulfillment of the Requirements for the Degree

MASTER OF SCIENCE IN SYSTEMS ENGINEERING

2008

Approved by

Dr. Scott E. Grasman, Advisor

Dr. Cihan H. Dagli

Dr. David Enke

© 2008

POORNA MARAPPA

All Rights Reserved

ABSTRACT

The dynamic nature of today's market drives the need for flexibility in supply chains. The ever-growing need for and importance of flexibility in supply chains has motivated researchers to develop frameworks to achieve supply chain flexibility. Much of the research on supply chain flexibility focuses on drivers of the need for flexibility and classification of supply chain flexibility. Existing frameworks for determining the desired degree of flexibility in supply chains give an overview methodology; however, a comprehensive framework is absent. This research proposes a comprehensive framework to quantify the desired degree of flexibility in supply chains and accordingly determine its associated configuration.

ACKNOWLEDGMENTS

I would like to take this opportunity to thank the people who have helped me accomplish this research effort. I am extremely grateful to my advisor, Dr. Scott E. Grasman, for providing me the opportunity to work in this interesting area, and for his unflinching support, advice and guidance throughout the work. I would like to thank my thesis committee members, Dr. Cihan H. Dagli and Dr. David Enke, for their insightful comments. I am grateful to the support and encouragement rendered by Dr. Durai Sundaramoorthi during this work, and also for participating in thought-provoking discussions. My thanks to colleagues and friends Amith B. Shetty, Mandar V. Joshi, and Shikha Chaudhary, for providing good company. My special thanks to Vicki Hudgins for helping me in formatting the thesis to perfection. My work would be incomplete without mentioning the efforts, encouragement and trust bestowed in me by my parents, who are a constant source of inspiration, my sister, who is a great companion, and the significant others, who believed in me more than anyone else.

TABLE OF CONTENTS

	Page
ABSTRACT.....	iii
ACKNOWLEDGMENTS	iv
LIST OF ILLUSTRATIONS.....	vi
LIST OF TABLES.....	vii
SECTION.....	
1. INTRODUCTION.....	1
2. BACKGROUND LITERATURE AND REVIEW ON SUPPLY CHAIN FLEXIBILITY FRAMEWORKS.....	4
3. FRAMEWORK FOR FLEXIBILITY DRIVERS.....	8
3.1 PROPOSED FRAMEWORK.....	8
3.2 DRIVING FLEXIBILITY AT EACH LEVEL OF THE SUPPLY CHAIN	10
3.2.1 Source (Supply)	10
3.2.2 Make (Manufacturing).....	11
3.2.3 Deliver (Logistics).....	12
4. SIMULATION AND MODELING METHODOLOGY.....	18
4.1 SIMULATION MODELS.....	18
4.2 DESIGN AND ANALYSIS OF SIMULATION EXPERIMENTS	20
5. SIMULATION RESULTS AND INSIGHTS.....	24
6. CONCLUSION AND FUTURE RESEARCH.....	31
APPENDICES	
A. MATHEMATICAL MODELS.....	32
B. DESIGN OF EXPERIMENTS.....	55
C. SIMULATION ANALYSIS RESULTS.....	60
D. SIMULATION CODE.....	86
BIBLIOGRAPY.....	109
VITA	113

LIST OF ILLUSTRATIONS

Figure	Page
3.1. SCOR model with systems that enable flexibility at each level of supply chain.....	9
3.2. Alternatives at each level of the supply chain.....	16
4.1. Simulation model for demand side inventory control system.....	18
4.2. Simulation model for decoupling point.....	20
4.3. Simulation model for supply side inventory control system.....	20

LIST OF TABLES

Table	Page
2.1. Existing frameworks on supply chain flexibility.....	6
4.1. List of ratios considered during simulation.....	21
5.1. Flexibility performance table for demand side inventory control policy.....	24
5.2. Flexibility performance table for supply side inventory control policy.....	26
5.3. Flexibility performance table for decoupling policy.....	28

1. INTRODUCTION

The emerging global market has placed a premium on the ability of companies to evaluate new market opportunities and introduce new products in order to respond quickly to customer requirements and remain competitive. Markets are becoming more global, dynamic, and customer driven, creating a turbulent, complex, and uncertain environment. In such an environment, competitive companies of the future must have the ability to sustain continuous change and respond to calls for dramatic change [1]. The uncertain and dynamic nature of markets drives the need for supply chains to be flexible because enterprises are expected to be agile and responsive due to the advancement of distributed information technology and the changing needs of the business community [2]. Hence, supply chains are faced with a situation in which they have to accept uncertainty, but need to develop a flexible strategy that enables them to match supply and demand [3]. However, the road to achieving successful flexibility strategy for supply chains is far from smooth. In a study conducted by Treville et al. [4], it was found that managers at many plants deemed an astounding 40% of flexibility improvement efforts to be unsuccessful and disappointing. The main reason for this is the fuzzy and complex construct of flexibility and misalignment of desired and achieved flexibility. Only by understanding the particular characteristics of the product type and market place requirements can the correct supply chain strategy be designed to ensure optimal performance. Therefore, there is a need to develop a framework or methodology to align the strategy of the supply chain with the flexibility needs of the industry [3].

Flexibility as the key dimension of supply chain performance has motivated researchers to define, classify and develop frameworks to achieve supply chain flexibility. Existing frameworks focus mainly on the classification of supply chain flexibility and market uncertainties that drive the need for flexibility at different levels of the supply chain. However, these frameworks propose only a brief methodology to achieve flexibility in supply chains and most of them fail to address the issue of the desired degree of flexibility. Therefore, it is necessary to bridge the gap by developing a comprehensive framework to not only quantify the desired flexibility of the supply chain

but also determine the optimum supply chain configuration to satisfy the flexibility needs.

This thesis presents a system engineering framework to determine the optimal configuration of the supply chain by quantifying the desired degree of supply chain flexibility. System Engineering is an interdisciplinary approach to design complex systems which satisfies the customer needs in terms of performance, schedule, risk, and cost. Due to the dynamic nature of the market and distributed nature of today's enterprises, supply chains are evolving to be complex systems. Moreover, there is also an ever-growing interest to increase customer satisfaction levels and keeping the operating costs low at the same time. Therefore there is a need to apply concept of system engineering to align supply chain design to market needs. Flexibility metrics (e.g., new product flexibility, product mix flexibility, volume flexibility, and delivery flexibility) have been identified from the existing literature for each of the market needs (e.g., frequent introduction of new products, product variety, ability to cope with demand fluctuations, and short delivery time) in order to quantify the desired degree of supply chain flexibility. Systems at each level of the supply chain that determine the supply chain configuration and their possible alternatives have been identified from the existing literature. Then modeling and simulation is used to determine the performance of the alternatives with respect to the drivers of supply chain flexibility.

This research contributes to the literature on supply chain flexibility follow in a number of ways. First, this research gives a system engineering perspective to align the supply chain design to the market needs. Second, the research identifies all the systems at each level of the supply chain that determines the supply chain configuration and also the possible alternatives for each of these systems. Third, the framework developed is more comprehensive; it not only quantifies the desired degree of flexibility for supply chains, but also determines the configuration of the supply chain.

The remaining sections of the thesis are organized as follows: Section 2 provides a comprehensive review of supply chain flexibility and agility frameworks. Section 3 introduces the proposed framework to achieve the desired degree of flexibility in supply chains and the deployment of flexibility at each level of the supply chain. Section 4 gives details about the systems at each level of supply chain that enable flexibility in supply

chains. Possible alternative policies or configurations for each of these systems have also been discussed in detail. Section 5 gives a detailed outline of the methodology used to determine the optimal configuration of the supply chain. Section 6 gives a description about the simulation models and the assumption made for each model. Section 7 gives details about the experiments that have been designed to compare the alternatives with respect to new product flexibility, product mix flexibility, volume flexibility and delivery flexibility. The results of the simulation are presented and discussed in detail in Section 8. Finally, conclusions are drawn and potential for future work is proposed in Section 9.

2. BACKGROUND LITERATURE AND REVIEW OF SUPPLY CHAIN FLEXIBILITY FRAMEWORKS

The vast literature on supply chain flexibility consists of numerous frameworks with different perspectives on incorporating flexibility in supply chains. Most of the frameworks focus only on manufacturing flexibility and its benefits to business performance. For example, the framework proposed by Swamidass and Newell [6] focuses on the relationship between manufacturing flexibility and business performance by conducting a study of 35 manufacturing firms. Later frameworks hypothesized that organizational flexibility was a function of product development, manufacturing, supply, and logistics flexibility, since flexibility in production systems is not alone sufficient for competing in a rapidly changing environment [7]. The conceptual model of supply chain flexibility by Duclos et al. [8] forms a theoretical foundation for analyzing supply chain flexibility by recognizing the cross enterprise nature of supply chain flexibility and the need to have flexibility strategies beyond firm boundaries.

The value chain flexibility model by Zhang et al. [9] provides an abstract understanding of value chain flexibility and its ability to cope with environmental uncertainties. It considers supply chain flexibility to be a function of product development, manufacturing, logistics, and spanning flexibilities. The flexibility levels of the supply chain are defined and further classification of each level is carried out. For example, product development is further classified into product concept, prototype, product, modification and new product flexibilities. Manufacturing flexibility is classified into machine, material handling, labor, routing, and volume and mix flexibilities. Logistics flexibility is classified into physical supply, purchasing, physical distribution, and demand management flexibilities, and spanning flexibility into information dissemination and strategy deployment flexibility. This framework provides a comprehensive classification of the flexibility from the top level of the supply chain to the lower levels.

The global supply chain agility model created by Swafford et al. [10] classifies supply chain agility as a function of flexibility in product development, sourcing, manufacturing, logistics, and information technology. Flexibility at each level of the supply chain is defined as a function of range and adaptability, whereas range is defined

as the number of flexible options that can be achieved with existing resources and adaptability is defined as the ability to change the existing number of states. The framework formulates dimensions of range and adaptability for each level of the supply chain and also derives metrics to measure supply chain agility and performance. The definitions of Swafford et al. for manufacturing, logistics, sourcing and information technology flexibilities are comprehensive, covering all attributes of flexibility.

Kumar et al. [11] proposes a three stage conceptual framework to implement and manage flexibility in supply chains. In the initial stage the degree of uncertainties faced by the organization and its ability to deal with uncertainties are identified by carrying out a SWOT (Strength, Weakness, Opportunity and Threat) analysis. After competitive analysis, organization goals and objectives are defined and flexibility requirements (e.g., product, volume, delivery, and new products) of the organization are ascertained. The second stage deals with the implementation of flexibility by assigning flexibility requirements to different levels of the supply chain and identifying strategies for implementation. The final stage is the feedback and control stage, in which required and observed flexibility are periodically measured and controlled. This ensures that flexibility continues to provide a competitive edge and positively influence supply chain performance.

Pujawan's [5] framework for assessing flexibility classifies supply chain flexibility into sourcing, product development, production, and delivery flexibilities. The drivers of the need for flexibility in supply chains are identified and mapped to each level of the supply chain. The intensity of relationships between keyed drivers and various levels of the supply chain is determined and weights are assigned accordingly, leading to the quantification of the desired degree of flexibility at each level of the supply chain. The degree of flexibility at each level is identified by conducting a survey and quantifying the results. Gap analysis is then carried out to determine the levels in the supply chain that require greater levels of flexibility. The thesis presents guidelines for conducting flexibility judgment and a case study to provide insights into the pertinence of the framework.

The existing frameworks used to achieve flexibility and agility in supply chains and their contribution to the literature on supply chain flexibility are summarized in Table

2.1. It is clearly evident that, there is a significant overlap in the frameworks summarized in Table 2.1, yet there is no agreement on the classification of supply chain flexibility.

Table 2.1. Existing frameworks on supply chain flexibility

FRAMEWORK	AUTHOR/YEAR	DESCRIPTION
A conceptual model of supply chain flexibility.	Duclos et al. 2003 [6]	Examination of classification schemes of supply chain flexibility published in the literature. Creation of a theoretical foundation for analyzing the components of supply chain flexibility.
Value chain flexibility; a dichotomy and competence.	Zhang et al. 2002 [7]	Classification of supply chain flexibility. Exploration of the relationship among environmental uncertainty, value chain flexibility and competitive advantage.
Global supply chain agility model and its impact on competitive performance.	Swafford et al. 2000 [8]	Classification of supply chain flexibility and development of dimensions for each of the flexibility levels. Definition and development of measures for supply chain agility and flexibility for each level of the supply chain.
Conceptual framework to develop and manage flexibility in supply chains.	Kumar et al. 2004 [9]	Presentation of a brief conceptual framework to implement and manage flexibility in supply chains.

Table 2.1. Existing frameworks on supply chain flexibility (cont.)

Assessing supply chain flexibility; a conceptual model and case study.	Pujawan 2004 [3]	Classification of supply chain flexibility. Identification of drivers of the need for flexibility. Determination of the desired degree of flexibility at each level of the supply chain.
--	------------------	--

Frameworks by Duclos et al. and Swafford et al. focus primarily on the taxonomy of supply chain flexibility without any consideration of the industry characteristics and other environmental factors. Zhang et al. considers environmental uncertainty in their study, but fails to address the issue of the desired degree of flexibility in supply chains. Pujawan's framework identifies the drivers of supply chain flexibility and determines the desired degree of flexibility at each level of the supply chain, but determining the optimal configuration of the supply chain is beyond its scope. It is evident here Table 2.1 from the literature that very little work has been done so far on the issue of flexibility implementation. Therefore, the framework is proposed quantifies the desired degree of supply chain flexibility and accordingly determines the optimal configuration of the supply chain.

3. FRAMEWORK FOR FLEXIBILITY DRIVERS

3.1. PROPOSED FRAMEWORK

The main aim of this research is to develop a framework to 1) quantify the desired degree of supply chain flexibility and 2) determine the optimal configuration of the supply chain based on the needs of the industry. In order to quantify the desired degree of supply chain flexibility, it is essential to identify drivers of supply chain flexibility and develop metrics to measure their intensity. As stated before, the need for flexibility is largely influenced by the operating environment of a supply chain. The literature on the drivers of supply chain flexibility illustrates both external and internal drivers of supply chain flexibility. While market needs are classified as external drivers of flexibility, operating characteristics are considered to be internal drivers. Slack [12] identified the external drivers of supply chain flexibility to be frequent introduction of new products, product variety, short lead time to market, output variation, and time/schedule changes and he developed flexibility metrics for these drivers. Similarly, Suarez et al. [13] identified and defined flexibility metrics to assist firms in implementing a particular optimal configuration or strategy. Hence the following flexibility metrics developed by Suarez et al. have been adopted:

1. New product flexibility: ability to introduce new products or changes to existing products by additions to the product mix over time;
2. Product mix flexibility: Ability of the system to produce different number of products at the same time;
3. Volume flexibility: ability of the system to change the total production level, in order to respond quickly to demand changes;
4. Delivery flexibility: ability to move planned delivery dates forward or backward;

The proposed framework, adopts the Supply Chain Operations Reference (SCOR) model to drive flexibility at different levels of the supply chain. The SCOR model is a process reference model that has been developed and endorsed by the Supply Chain Council as the cross-industry standard diagnostic tool for supply chain management [14]. The SCOR model describes the business processes (supply chain levels), i.e., source, make, deliver and return, required to satisfy the customer's demand and it can be used to

represent supply chains of disparate industries. Having adopted the SCOR model for identifying the different levels of the supply chain, it is essential to investigate the systems that determine the supply chain configuration. In reviewing the literature for systems that enable flexibility in the source, make, deliver functions of the supply chain, the following systems have been identified: supplier collaboration, supply side inventory control policy, manufacturing system, production planning and control system, decoupling point, distribution network, and demand side inventory control policy. Figure 3.1 illustrates levels of the supply chain based on the SCOR model and the systems at each level that determine the supply chain configuration.

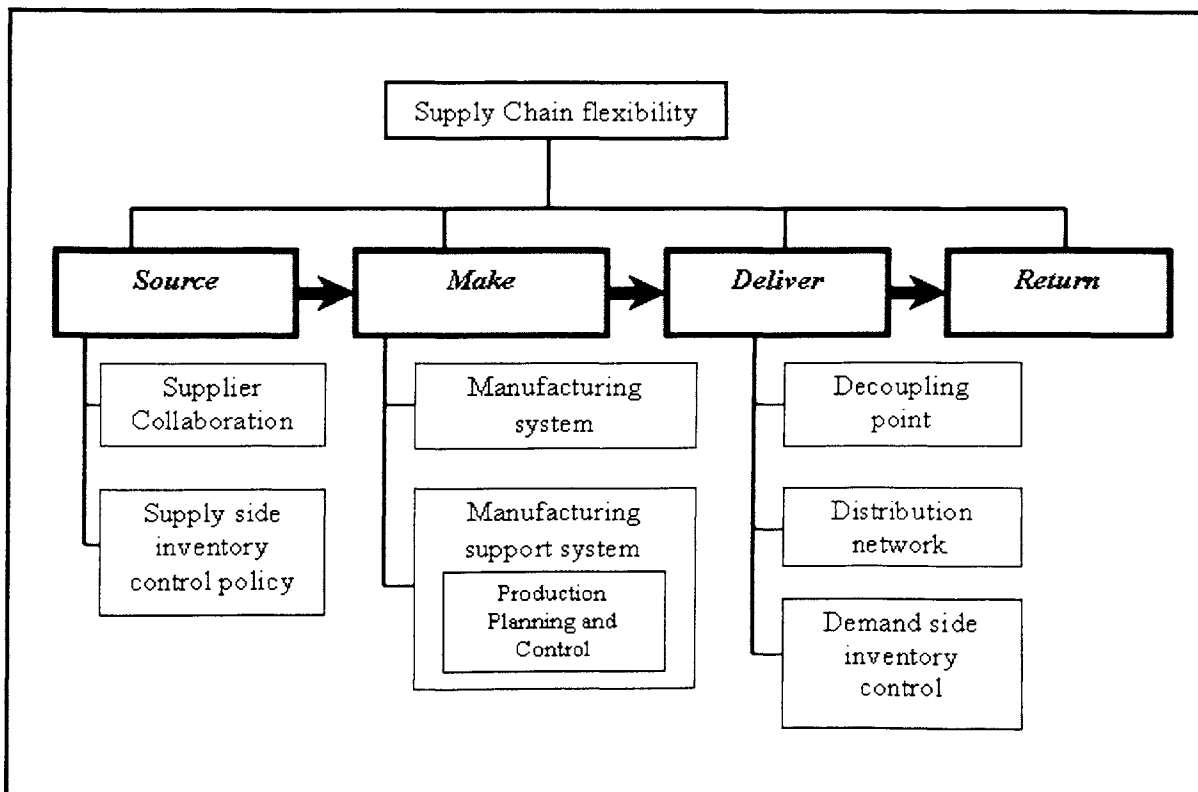


Figure 3.1. SCOR model with systems that enable flexibility at each level of supply chain

Each of these systems will be discussed in the following sections.

3.2. DRIVING FLEXIBILITY AT EACH LEVEL OF THE SUPPLY CHAIN

In this section the systems at each level of the supply chain that determine supply chain configuration have been addressed and the alternatives for each of these systems is have also been discussed.

3.2.1. Source (Supply). One of the keys to achieving agile response to fast changing markets lies upstream from the organization in the quality of supplier relationships [15]. Bensaou [7] states that successful supply chain management requires the effective and efficient management of relationships: first, firms must match the optimal type of relationship to the various product, market and supplier conditions: second, they must adopt the appropriate management approach for each type of relationship. Integrating sourcing with supply chain management supports an organizations ability to deliver products and services in a timely, effective manner [16], thereby increasing supply chain flexibility. Therefore, flexibility at the supply level of the supply chain is mainly a function of the collaboration strategy adopted with suppliers and the supply side inventory control policy. Austin and Lee [17] found that companies in the PC industry are engaged in extensive collaborative efforts with suppliers to reduce the risks of material shortages during the product introduction phase and overproduction at the end of the product lifecycle.

Types of collaborative relationships with suppliers include, 1) information exchange, 2) supplier managed replenishment, and 3) convenient partnerships. Collaboration through information exchange is done by sharing demand information such as point of sales data with suppliers. Such information would help to reduce the echelon inventory levels and reduce risk of stock outs and excess inventory. In the case of supplier managed replenishment, collaboration is much more than just information sharing. The supplier generates the replenishment order and takes responsibility for maintaining the manufacturer's inventory. Convenient types of partnerships with suppliers do not involve any collaboration, and are often maintained by joining e-consortiums to create a dynamic supplier base. Convenient partnerships lead to volume

flexibility, but conflicting goals might lead to higher inventory levels within the supply chain. Collaborative relationships with suppliers would not only help to reduce echelon inventory, but also to increase the availability of raw materials or components.

Flexibility performance at the supply level of the supply chain is also a function of supply side inventory control policy. These policies should be well managed and coordinated among the members of the supply chain to ensure desired customer service levels. Alternative inventory management policies include, 1) Material Requirement Planning (MRP), 2) order point system, and 3) Kanban. Material Requirement Planning (MRP) is a time phased replenishment approach based on the anticipated demand. Inventory status is reviewed periodically and orders are placed to the upstream members of the chain. The order point system, on the other hand, is an inventory control system that operates on logic where replenishment orders are placed when the inventory falls below the predetermined order point. Finally, the kanban system which gained popularity in the 1980s, utilizes improved information technology and emphasis on organizational integration and co-ordination. The main goal of the kanban system is to ensure that the right quantity arrives at the right place at the right time. The operating logic of the kanban system is similar to pull logic, but the main focus here is to minimize inventory at the cost of placing frequent orders. Therefore, integration and co-ordination with suppliers to reduce ordering costs is essential.

3.2.2. Make (Manufacturing). Flexibility is widely recognized as a key component of successful manufacturing strategy and is defined as the capability of a firm to quickly and economically respond to various types of environmental uncertainty [18]. Flexibility in the manufacturing level of the supply chain can be achieved through both technology and human resources. The “technology approach” to achieving flexibility at the manufacturing level of the supply chain involves the use of automation, such as Flexible Machine Systems (FMS), automated material handling systems, real time process control systems, and rapid prototyping tools such as computer aided machining (CAM). Many manufacturing firms are now investing in flexible manufacturing systems (FMS) in an attempt to improve their responsiveness to unforeseen changes in product markets and manufacturing technology [19]. Manufacturing flexibility can also be delivered by human resources. The larger the range of skills of a worker, the more

flexible he or she is, either in terms of a mix of products or in terms of the interchangeability of workers between workstations [20]. Therefore, flexibility at the manufacturing level of the supply chain is a function of manufacturing and manufacturing support systems.

Configuration of the manufacturing system determines the degree of automation of machines, material handling systems, and their layouts. Different configurations of manufacturing systems available are, automated transfer lines, job shop, flexible manufacturing systems, agile reconfigurable cells, and manufacturing cells. Each of these manufacturing system configurations have different degrees of associated flexibility. Therefore, the selection of a specific manufacturing system configuration is depends on the degree of flexibility desired.

The manufacturing support systems enable the system to be responsive to market demand fluctuations. The production planning and control system is the interface of the manufacturing system with the upstream and downstream members of the supply chain. Production planning systems can be broadly classified into schedule based and quantity based systems. Schedule based systems, also known as push systems, determine the starting and finishing times of operations based on lead time offset. Examples of schedule based systems include, Manufacturing Resource Planning (MRP) and Optimized Production Technology (OPT). The quantity based or pull systems maintain buffer inventory levels for each of the manufacturing operations and orders are triggered when the inventory falls below a pre-determined point. Examples of the quantity based systems are Kanban, Constrained Work in Process inventory (CONWIP) and Theory of Constraints (TOC).

3.2.3. Deliver (Logistics). The delivery level of the supply chain enables superior customer service by synchronizing product delivery to customer demands [21]. Flexibility at this level of the supply chain can be accomplished by planning and controlling the flow and storage of goods from their point of origin to consumption. The capabilities of physical distribution and demand management are strategically important because they enable firms to meet the needs of the eventual customers [22]. Therefore, the positioning of the decoupling point, type of distribution network, and the demand side

inventory control policy determine the flexibility performance at this level of the supply chain.

Postponement has been considered an important method for attaining both mass customization and agility [23]. Jones et al. [3] define the decoupling point as the point in the material flow streams to which the customer order penetrates. It is basically the junction at which the forecast and order driven (push and pull) activities meet through the postponement of product differentiation. The position of the decoupling point is probably the single most important decision in supply chain configuration due to its impact on the flexibility performance of the entire supply chain. Available alternatives for the decoupling point are 1) make-to-stock (MTS) supply chain, 2) assemble-to-order (ATO) supply chain and 3) make-to-order (MTO) supply chain. In a make-to-stock supply chain, materials are pushed downstream to the distributor or retailer based on the demand forecast. Therefore, product differentiation takes place at the manufacturing or assembly process. Accurate forecasting by all members of the supply chain is critical in order to achieve a high service level and reduce overstocks [24]. In the case of an assemble-to-order supply chain, customization is postponed to the assembly stage. This is an effective strategy for responding to varying product mixes and overstocks due to product obsolescence. Finally, in the case of a make-to-order supply chain, the decoupling point is pushed back to the manufacturer. Since the product is manufactured only for real customer orders, lead time for replenishment of customer orders increases, but there is an increase in the ability to cope with product mix and demand fluctuations.

The type of distribution network determines the responsiveness of the supply chain to customer needs and the cost incurred to achieve it. There are five different distribution network types, namely, 1) retail storage with customer pick-up, 2) manufacturer storage with in-transit merge, 3) distributor storage with package carrier delivery, 4) distributor storage with last mile delivery and 5) manufacturer storage with direct shipping [25]. Each of the distribution networks have different degrees of customer service and deployment costs associated with them. In the case of manufacturer storage with a direct shipping network, products are shipped directly to customers, thereby eliminating the need for a distribution center. Manufacturer storage with direct shipping and in- transit merge is similar to the previous networks, except for the in-transit merge.

This network is used in situations where the customer order consists of products from different manufacturers. The in-transit merge activities are usually outsourced to third party service providers due to high facility and processing costs. In a distributor storage and carrier delivery network, inventory is maintained in a warehouse by the distributor and shipped to customers. Distributor storage with last mile delivery is a home delivery network with distribution centers located close to the customers. This network requires high inventory levels due to low levels of aggregation in inventory. Retail storage with customer pick up is a standard network used by most companies. In this case, the inventory is stored locally at the retail stores. The selection of the distribution network will determine the type of transportation mode and warehouse. Therefore, a network designer needs to consider market needs and the product characteristics before deciding on a specific distribution network.

The delivery function of the supply chain also involves demand side inventory management. Inventory control policies determine the way inventory levels are maintained across the supply chain. These policies should be well managed and coordinated among the members of the supply chain to ensure desired customer service levels. Distribution Requirement Planning (DRP) and order-point replenishment are two types of inventory control policies. Distribution Requirement Planning (DRP) is a time-phased replenishment approach with an operational concept similar to that of Material Requirement Planning (MRP). Based on the anticipated demand, inventory status is reviewed periodically and orders are placed to the upstream member of the chain. The order point system, on the other hand is a pull type inventory control system where replenishment orders are placed when the inventory falls below the predetermined order point. Order point systems are considered to be reactive because they often use average information for the replenishment decisions and do not have mechanisms to anticipate the changes in demand [26].

Figure 3.2 shows all the systems at each level of the supply chain and the alternatives for each of these systems that have been discussed in this section. Therefore, in order to drive the flexibility needs of the industry to the supply chain design, 1) Flexibility metrics have to measure the flexibility needs of the supply chain have been identified, 2) Systems at each level of the supply chain that enable flexibility have been

determined, and finally in this section, 3) Alternatives for each of the supply chain systems have been enumerated. Using this framework, the configuration of the supply chain can be aligned to the flexibility needs of the industry.

In order to implement the proposed framework, the performance of the alternatives for each of the above mentioned systems should be compared with respect to the flexibility metric. Discrete event simulation is used to compare the performance of the alternatives with respect to, new product flexibility, product mix flexibility, volume flexibility and delivery flexibility. Discrete event simulation, a powerful tool to compare alternative real time systems prior implementation, is used to evaluate the operating performance of these alternatives [27]. Discrete event simulation models can represent system behavior in detail and can represent material flow, information flow and combination of both [28]. . The performance of any supply chain system is measured based on the service level or fill rate and the total inventory cost which involves the ordering, holding and backorder costs.

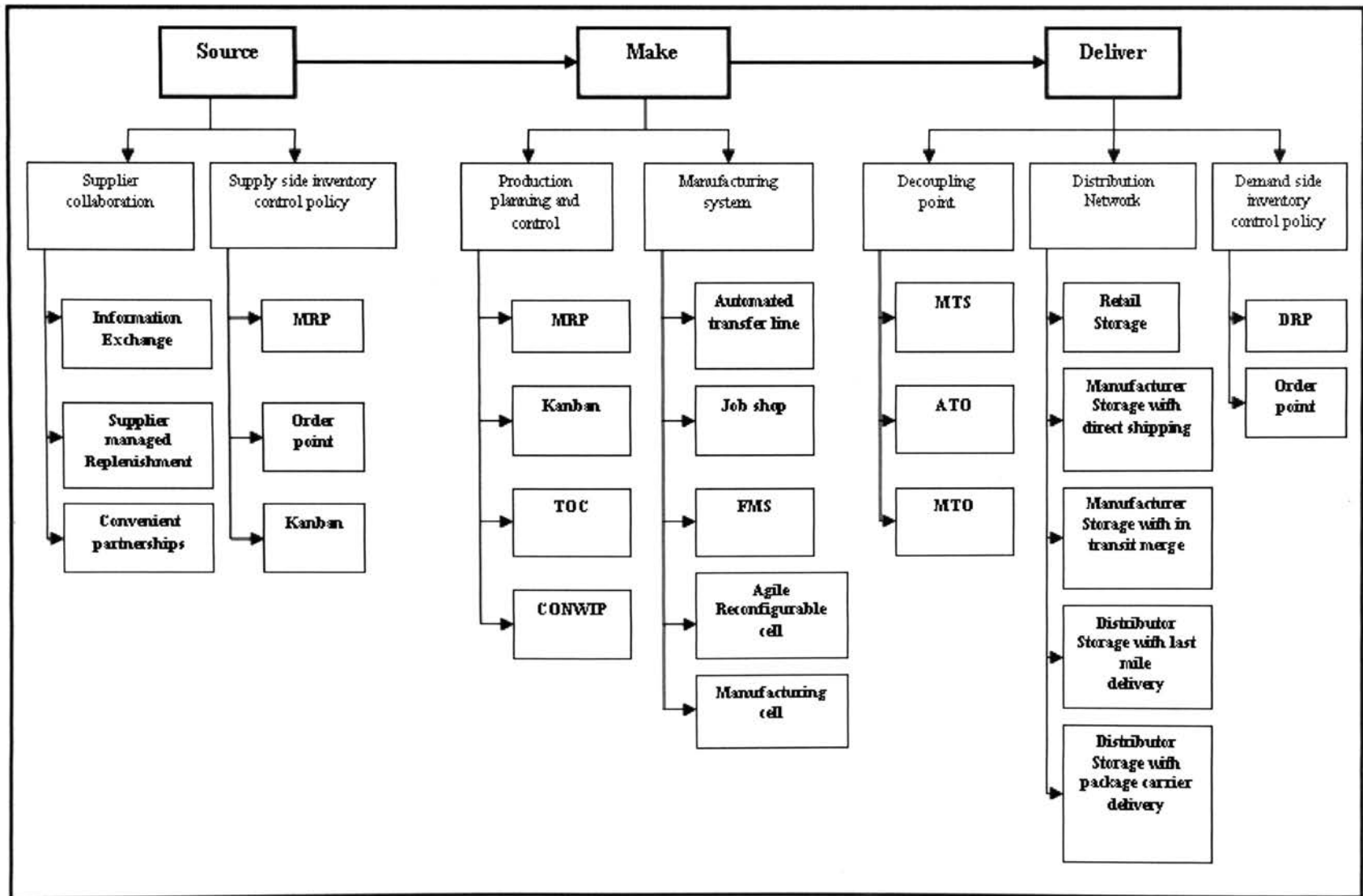


Figure 3.2 Alternatives at each level of the supply chain

Kleijnen et al. [29] list all the supply chain performance metrics used in the industry to measure the logistical performance. Fill rate and inventory cost are the critical performance metrics used to compare supply chain systems. High service level is desired, but cost is also equally important. An alternative might achieve the desired service level, but the cost of achieving the desired service level might be high. Such an alternative is considered to be less flexible as compared to the one which achieves the same service level with low cost. On the other hand, some alternatives might achieve relatively low service levels, but the costs could also be significantly low. Such an alternative might be preferred to one with relatively high service level and cost. It is therefore very important to strike the right balance between the service level and cost. Therefore the ratio of service level by cost, known as flexibility index, is used to measure the flexibility. Let N_{BO} be the average back order quantity and N be the total demand, then fill rate or service level is determined as shown below. Let C be the total inventory cost obtained from the cost model, then Flexibility index α is given by the formula shown below.

$$r = 1 - (N_{BO} / N) \quad (1)$$

$$\alpha = r / C \quad (2)$$

This performance metric is used to compare the performance of the alternatives across all systems of the supply chain. Out of the seven systems mentioned above that determine the configuration of the supply chain; only three systems are considered to implement our framework: demand side inventory control, supply side inventory control and decoupling point. These systems have been considered to implement the framework because, 1) Ease of modeling these systems, and 2) Other systems need lot of data and complex analysis required to derive conclusions. Modeling and simulation of these systems is carried out in Matlab 7.1. The simulation code for these systems is as shown in Appendix D.

4. SIMULATION AND MODELING METHODOLOGY

4.1. SIMULATION MODELS

In this section, the simulation models that have been developed is discussed in detail, 1) Demand side inventory control policy, 2) Decoupling point, and 3) Supply side inventory control policy, that have been developed to implement the framework. The demand side inventory control model is developed for a single distributor-retailer network scenario as shown in Figure 4.1. The distributor supplies products $i = 1 \dots p$ to the retailer based on the orders placed by the retailer. Many researchers have found that use of safety stock can help reduce nervousness of DRP/MRP systems to demand uncertainty. Hence, the safety stock with rolling horizon policy for the MRP system used by Zhao et al. [30] in their study to evaluate safety stock methods in multi-level MRP systems has been adopted. The DRP with safety stock and rolling horizon policy has been adopted for the Distribution Requirement Planning (DRP) model and min-max inventory control policy for the Order point system. The min-max system of inventory control is the most popular of all the inventory control procedures [31]. Therefore, the min-max policy has been adopted to model an order point pull system. The following assumptions have been made to avoid complexity in the model: 1) lead times are deterministic, 2) Manufacturer supplies products to distributor on time, and 3) Customer waits for delayed orders.

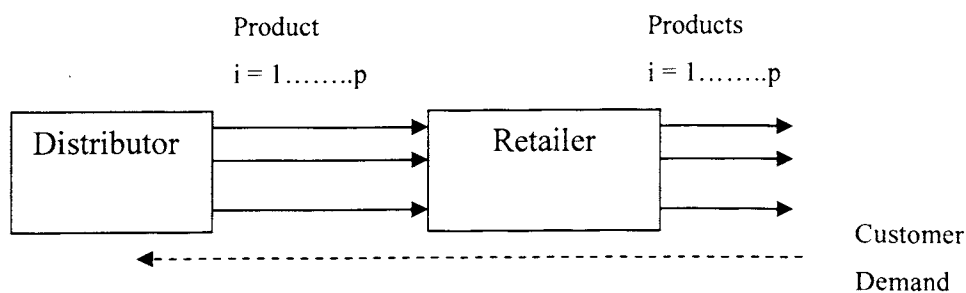


Figure 4.1. Simulation model for demand side inventory control system

Decoupling point as described before determines the point where product differentiation. Lee et. al [32] model the costs and benefits of delayed product differentiation and discuss three approaches of postponement, 1) standardization; 2) modular design; and 3) process restructuring. The first two approaches require changes in the manufacturing equipment and product redesign which involve some investment cost. The process restructuring approach is just about postponing the operation, by conducting it after the customer order arrives. Therefore, the process restructuring is considered in the approach to evaluate decoupling point configurations.

The exposition of our model for decoupling point is simplified by developing a model for a supplier-manufacturer-assembler-distributor scenario, as shown in Figure 4.2. The supplier supplies raw materials $j=1, \dots, m$, to the manufacture to produce work in process inventory $k=1, \dots, w$. The min-max inventory control has been adopted for all the decoupling point alternatives. The following assumptions are made to simplify the model: 1) lead times are deterministic, 3) customer waits for delayed orders, and 4) unlimited supply of raw materials for the supplier. The performance the alternative configurations is dependent on the processing costs at the manufacturing and assembly stage, since they determine the inventory holding costs at the stocking points. Running the simulation for only one particular case of processing cost at the assembly and manufacturing phase will create a bias. In order to eliminate the bias, different scenarios of processing cost at manufacturing stage and assembly stage are considered. The cost model developed by Lee et al. [32] is used to compare the alternative configurations.

The supply side inventory control model is developed for a single supplier-manufacturer scenario as shown in Figure 4.3. The supplier supplies components, $j=1 \dots m$ to the manufacturer to manufacture products $i=1 \dots p$. Demand generated for the finished products and then driven to the components based on the bill of materials structure. Similar to the demand side inventory control policy, a safety stock with rolling horizon policy for the MRP system used by Zhao et al. [30] in their study to evaluate safety stock methods in multi-level MRP systems has been adopted. Assumptions made in the model are: 1) supplier has unlimited quantity of raw materials, and 2) deterministic lead time for manufacturing and transportation. The mathematical models that have been used in simulation are described in detail in Appendix A.

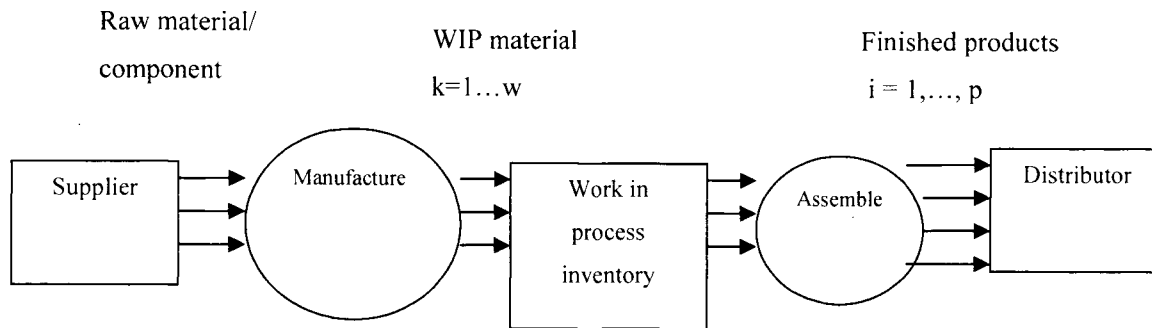


Figure 4.2. Simulation model for decoupling point

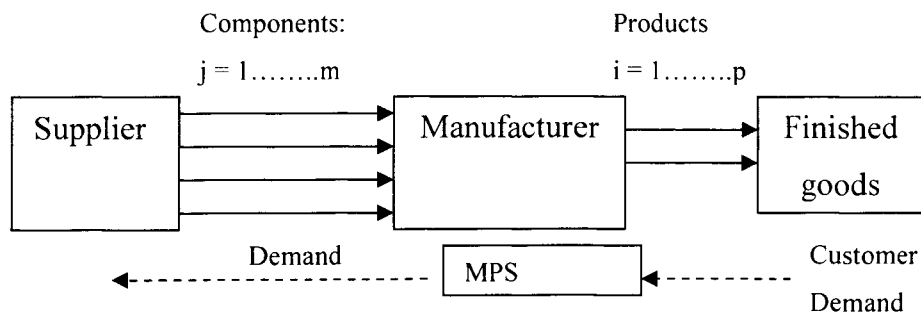


Figure 4.3 Simulation model for supply side inventory control system

4.2. DESIGN AND ANALYSIS OF SIMULATION EXPERIMENTS

As discussed in the methodology, there is a need to determine the flexibility of the alternatives with respect to the drivers of supply chain flexibility. Therefore, experiments have been designed to determine the volume flexibility, delivery flexibility, product mix flexibility and new product flexibility of the alternative supply chain systems. The alternatives for each of these systems shall be compared used flexibility metric called flexibility index as discussed in the previous section. The ordering cost and holding cost ratio and the penalty cost to holding cost ratio have significant effect on the cost models

of the supply chain systems that have been considered which intern affects the flexibility index. Hence, the ratios shown below in Table 4.1 are varied and simulation is carried out for each of experiments for 12 different combinations of the ratios.

Frequent introduction of new products increases market dynamics, driving the need for supply chain flexibility. Fisher [33] devised a simple framework to determine the right supply chain for the product, in which he classified products based on the length of their lifecycle and demand characteristics. Products having a very short life cycle of 6 months to one year are classified as innovative products, and the forecasting error range is 40-100%. On the other hand, functional products with a life cycle of more than 2 years haven an average forecasting error of 10%.Using the product life cycle demand curve and the forecast error range for innovative and functional products devised by Fisher [32], demand cycles are generated for products with life cycle of 1 year, 2 years and 3 years, respectively

Table 4.1. List of ratios considered during simulation

Ordering cost/ Holding cost (K/H)	10	50	100	500
Penalty cost/ Holding cost (B/H)	20	60	100	

The alternative supply chain systems are compared for 36 test problems (4 ordering cost to holding cost levels, 3 penalty to holding cost ratios, 3 product life cycle levels). The inputs to determine the new product flexibility is as shown in table 1 of Appendix B.

To determine the product mix flexibility of the alternatives, the number of products in the system and volume of demand is correspondingly varied. Heterogeneous and homogenous demand scenarios for each case (number of products) have also been

generated. The alternative supply chain systems are compared for 180 test problems (4 ordering cost to holding cost levels, 3 penalty to holding cost ratios, 3 number of product levels and 5 sublevels for each product mix level). The inputs to determine the product mix flexibility is as shown in table 2 of Appendix B.

In this experiment, the volume flexibility measure considers only the costs associated to meet the volume fluctuations. Input demand is assumed to be a normal distribution and is varied from low to high. In this case, the main concern is only the cost associated in meeting the demand and are not the degree of demand uncertainty; hence the following assumptions are made, 1) Forecasted demand and actual demand is assumed to be the same, and 2) the standard deviation of the demand is also kept constant for all degrees of demands. The alternative supply chain systems are compared for 60 test problems (4 ordering cost to holding cost levels, 3 penalty to holding cost ratios, 5 product demand levels). The inputs to determine the volume flexibility is as shown in Table 3 of Appendix B.

Delivery flexibility allows the supply chain to accommodate rush orders and special orders Therefore, forecasting error is used to model the demand fluctuation that occurs due the changes in the order dates. The forecasting error is increased from low to high and the flexibility index is calculated for each case. The alternative supply chain systems are compared for 96 test problems (4 ordering cost to holding cost levels, 3 penalty to holding cost ratios, 8 demand uncertainty levels). The inputs to determine the volume flexibility is as shown in Table 4 of Appendix B.

In order to statistically compare the alternatives for different scenarios, the paired-t confidence interval approach has been used for two alternative designs and the Bonferroni approach for comparing more than two alternative system designs. For each experiment, 30 replications are simulated and the above mentioned approaches are used for analysis. In the paired-t confidence interval approach to compare the performance of two systems, difference between the performances of the alternative systems is calculated for each replication and the sample mean and standard deviation is determined. The sample mean and standard deviation is then used to calculate the confidence interval with 95% confidence. If the confidence interval ranges from negative to positive, it is considered that performances of both the systems are the same for that particular case. On

the other hand, if the confidence interval range is either negative or positive it is concluded that one of the alternatives is better than the other for that particular case. The Bonferroni approach is useful for comparing three to about five designs or alternatives [34]. The Bonferroni approach is very similar to the t- confidence interval approach. The Boniferroni method is implemented by constructing a series of confidence intervals to compare alternatives. If K is the number of alternatives, then the number of confidence intervals for pair wise comparisons is given by the formula: $K*(K-1)/2$. The logic for deciding whether there is a significant difference between the performances of the systems is same as the paired-t confidence interval approach.

5. SIMULATION RESULTS AND INSIGHTS

This section presents the results and insights obtained from the simulation experiments and statistical analysis that have been performed. The conclusions from the simulation results shown in Appendix C for demand side inventory control policy are as shown in Table 5.1. In the case of the demand side inventory control policy, it is clearly evident from the simulation results that the performance of the order point performs better than the DRP when demand flexibility is low, but DRP performs better when high demand flexibility is desired. The order point is a better option than DRP when demand medium and high, since it can take demand uncertainty due to the buffer stock. It is also observed that when the demand and number of products increases, performance of the order point deteriorates significantly due to the high inventory holding costs. With respect to new product flexibility, distribution requirement planning performs better for products with long life cycles mainly because of the low demand uncertainty, while order point performs better for products with short lifecycles. Overall the order point policy performs better than the DRP in terms of service level; it's only the inventory holding cost that affects the performance of the order point when demand and product variety increases.

Table 5.1. Flexibility performance table for demand side inventory control policy

	LOW
Demand flexibility	ORDER POINT
Delivery flexibility	DRP
Product mix flexibility	ORDER POINT
New product flexibility	DRP

Table 5.1. Flexibility performance table for demand side inventory control policy (cont.)

	MEDIUM
Demand flexibility	DRP
Delivery flexibility	ORDER POINT
Product mix flexibility	DRP
New product flexibility	ORDER POINT
	HIGH
Demand flexibility	DRP
Delivery flexibility	ORDER POINT
Product mix flexibility	DRP
New product flexibility	ORDER POINT

In the case of the supply side inventory control policy three alternatives, i.e., Material Requirement Planning (MRP), kanban and order point, are compared. The conclusions from the simulation results shown in Appendix C for the supply side inventory control policy are as summarized in the Table 5.2. In this system, it is observed that order point consistently performs better than the Kanban and MRP in terms of demand flexibility, because of the low inventory levels. The order point system performs better than the MRP and kanban when the demand uncertainty increases because of the lead time buffer stock. Therefore, if high level of delivery flexibility is desired then order point system would be preferred. In the case of product mix flexibility, kanban perform better than the MRP and the order point, because of the low inventory levels. Kanban also performs better than the MRP and order point when a product with long life cycles, but as the product life cycle decreases, order point system performs better than kanban and MRP.

Table 5.2. Flexibility performance table for supply side inventory control policy

	LOW
Demand flexibility	ORDERPOINT
	KANBAN
	MRP
Delivery flexibility	KANBAN
	MRP
	ORDER POINT
Product mix flexibility	KANBAN
	MRP
	ORDERPOINT
New product flexibility	KANBAN
	MRP
	ORDERPOINT

	MEDIUM
Demand flexibility	ORDERPOINT
	KANBAN
	MRP
Delivery flexibility	ORDERPOINT
	KANBAN
	MRP
Product mix flexibility	KANBAN
	MRP
	ORDERPOINT
New product flexibility	ORDERPOINT
	KANBAN
	MRP

Table 5.2. Flexibility performance table for supply side inventory control policy (cont.)

	HIGH
Demand flexibility	ORDERPOINT
	KANBAN
	MRP
Delivery flexibility	ORDERPOINT
	KANBAN
	MRP
Product mix flexibility	KANBAN
	MRP
	ORDERPOINT
New product flexibility	ORDERPOINT
	KANBAN
	MRP

The positioning of the decoupling point is one of the most important decisions in supply chain design, since it has a significant affect on the flexibility performance of the entire supply chain. As discussed before, the simulation has been run for 4 different scenarios of manufacturing processing cost to finished goods holding cost ratio and assembly processing cost to finished goods holding cost ratio. Table 5.3 summarizes the rankings of the alternatives for different degrees of demand, delivery, product mix and new product flexibility. It is observed from the simulation results that as the demand increases, the make-to-order alternative performs better than the assemble-to-order and make-to-stock alternatives. This can be mainly attributed to low inventory holding costs of raw materials. Delivery performance of the assemble-to-order chain is observed to be better than the make-to-order and the make-to-stock configurations, since it strikes the right balance between inventory costs and service level. In the case of product mix flexibility it is again observed that assemble-to-order chain performs better than the other configurations for all degrees, i.e., low, medium and high of product mixes. Assemble-to-

order configuration outperforms the make-to-order and make-to-stock options, even with respect to new product flexibility. From the simulation output graphs, it is clearly observed that, postponement of processes adding less value to the product can significantly increase the flexibility of the supply chain. On the other hand, postponement of high value adding process might be detrimental to the performance of the supply chain. It is observed in the decoupling point configuration that the assemble-to-order option performs better than the other alternatives for most of the cases; therefore, further study is necessary to validate this result.

The results from the simulation and statistical analysis that have been tabulated can be used to configure the supply chain based on the flexibility needs of the industry. The tables give insight on which alternative performs the best for different degrees of the flexibility metrics. Therefore, once the desired degree of flexibility is quantified, the best alternative for each of the systems can be determined.

Table 5.3. Flexibility performance table for decoupling point

	LOW
Demand flexibility	ASSEMBLE-TO-ORDER
	MAKE -TO-ORDER
	MAKE-TO-STOCK
Delivery flexibility	ASSEMBLE-TO-ORDER
	MAKE-TO-ORDER
	MAKE-TO-STOCK
Product mix flexibility	ASSEMBLE-TO-ORDER
	MAKE-TO-STOCK
	MAKE-TO-ORDER
New product flexibility	ASSEMBLE-TO-ORDER
	MAKE-TO-STOCK
	MAKE-TO-ORDER

Table 5.3. Flexibility performance table for decoupling point (cont.)

	MEDIUM
Demand flexibility	ASSEMBLE-TO-ORDER
	MAKE -TO-ORDER
	MAKE-TO-STOCK
Delivery flexibility	ASSEMBLE-TO-ORDER
	MAKE-TO-ORDER
	MAKE-TO-STOCK
Product mix flexibility	ASSEMBLE-TO-ORDER
	MAKE-TO-ORDER
	MAKE-TO-STOCK
New product flexibility	ASSEMBLE-TO-ORDER
	MAKE-TO-STOCK
	MAKE-TO-ORDER
	HIGH
Demand flexibility	ASSEMBLE-TO-ORDER
	MAKE -TO-ORDER
	MAKE-TO-STOCK
Delivery flexibility	ASSEMBLE-TO-ORDER
	MAKE-TO-ORDER
	MAKE-TO-STOCK
Product mix flexibility	ASSEMBLE-TO-ORDER
	MAKE-TO-ORDER
	MAKE-TO-STOCK
New product flexibility	ASSEMBLE-TO-ORDER
	MAKE-TO-ORDER
	MAKE-TO-STOCK

For example, consider the automotive industry which needs low delivery and demand flexibility, high product mix flexibility and medium new product flexibility, Table 5.1 recommends order point for low demand flexibility, DRP for low delivery flexibility, DRP for high product mix flexibility, and order point for medium new product flexibility. In such scenarios it is difficult to decide between the alternatives and further insight into the simulation results is desired. It is observed from the simulation results that DRP significantly outperforms the order point when high product mix flexibility is required. On the other hand, there is no significant difference between the DRP and orderpoint when demand flexibility is low and delivery flexibility is medium. Therefore, DRP would be a better option for the demand side inventory control policy for the automobile industry.

For the supply side inventory control policy Table 5.2 recommends order point for low demand flexibility, kanban for low delivery flexibility and high product mix flexibility and order point for medium new product flexibility. In this case, high product mix flexibility is required, and kanban significantly outperforms the order point for high product mix flexibility and in situations where order point wins, it is seen that order point does not outperform kanban significantly. Therefore, kanban would be the best option for the automobile industry.

In the case of the decoupling point, Table 5.3 recommends assemble-to-order alternative for low demand and delivery flexibility, high product mix flexibility and medium new product flexibility. Therefore, assemble-to-order is the best alternative for the automobile industry.

6. CONCLUSION AND FUTURE RESEARCH

In the existing literature on supply chain flexibility, there has been no attempt made to determine the configuration of the supply chain based on the market needs. This research has proposed and implemented a framework that can be used to drive the desired level of flexibility in the supply chain configuration. This framework not only quantifies the desired degree of supply chain flexibility but also aligns the supply chain configuration accordingly. The performance of these alternatives with respect to the drivers of supply chain flexibility is also studied. Experiments have been designed and statistical analysis conducted to compare the performance of the alternatives with respect to the drivers of supply chain flexibility. Finally, this study serves as a starting point to determine the configuration of the supply chain based on the market needs. The simulation models that have been developed assume, a single manufacturer-supplier and distributor-retailer network, normal distribution for demand and deterministic lead times. Therefore, further study with many standard supply chain networks and demand distributions is essential before suggesting alternatives for different degrees of the flexibility metrics. The scope of the study also needs to be scaled by applying a similar simulation study to the other supply chain systems that enable at the respective supply chain levels.

APPENDIX A
MATHEMATICAL MODELS

This appendix consists of the mathematical models that have been developed for all the alternatives of the following systems, 1) Demand side inventory control policy, 2) Supply side inventory control policy, and 3) Decoupling point.

DEMAND SIDE INVENTORY CONTROL POLICY

Index

t	Time period
i	Product index
n	Number of time period
p	Number of products
Input variables	Retailer
x^r	Planning period for retailer
z^r	Frozen interval for retailer
M_i^r	Maximum level of inventory of product i at retailer
SS_i^r	Safety stock for product i at retailer
LT^r	Lead time for transportation of goods from distributor to retailer
S_{it}^r	Safety stock for product i at retailer at time t
SR_{it}^d	Scheduled receipts by distributor at for product i at time t
SB_{it}^d	Scheduled receipts for back orders from distributor for product i at time t
D_{it}^r	Actual demand for product i at time t at the distributor
F_{it}^r	Forecasted demand for product i at time t at the distributor
d_i^r	Mean demand at for product i at the distributor (forecast)
C_{iBO}^r	Penalty cost per unit back order for product i at retailer
PO_{it}^r	Purchase orders for product i at time t
O_{it}^r	Planned orders for product i at time t
Q_i^r	Economic Order Quantity for product I at retailer
RP_i^r	Reorder point for product i
s_i^r	Standard deviation of demand for product i at retailer
SL_i^r	Service level for product i at retailer
BO_t^r	Back order quantity for product i at time t
K_i^r	Ordering cost for product i at retailer

h_i^r	Inventory holding cost for product i at retailer
Input variables	Distributor
x^d	Planning period for distributor
z^d	Frozen interval for distributor
M_i^d	Maximum level of inventory for product i at distributor
SS_i^d	Safety stock for product i at distributor
LT^d	Lead time for replenishment of orders by manufacturer
S_{it}^d	Stock at distributor for product i at time t
SR_{it}^m	Scheduled receipts for product i at time t by manufacturer
D_{it}^d	Actual demand for product i at time t at the distributor
F_{it}^d	Forecasted demand for product i at time t at the distributor
d_i^d	Mean demand for product i at time t at the distributor
C_{iBO}^d	Cost of unit back order of product i at distributor
PO_{it}^d	Purchase orders for product i at time t by distributor
O_{it}^d	Planned orders for product i at time t by distributor
RP_i^d	Reorder point for product i at distributor
s_i^d	Standard deviation for product i at distributor
SL_i^d	Service level for product i at distributor
Q_i^d	Economic Order Quantity for product i at distributor
BO_{it}^d	Back order quantity for product i at time t at distributor
h_i^d	Inventory holding costs for product i at distributor
K_i^d	Ordering costs for product i at distributor
Output variables	
N_i^r	Total number of purchase orders from retailer to distributor for product i
N^r	Total number of purchase orders placed by retailer
N_{BO}^r	Total number of back orders at retailer
N_i^d	Total number of purchase orders from distributor to

	manufacturer for product i
I_i^r	Average level of inventory at retailer for product i
I^r	Average level of inventory at the retailer
I_i^d	Average level of inventory at the distributor for product i
I^d	Average level of inventory at the distributor
BO_i^r	Total number of back orders for product i at the retailer
C^r	Total cost of maintaining inventory at the retailer
C^d	Total cost of maintaining inventory at the distributor
r^r	Fill rate of retailer
α	Flexibility index

Retailer

Economic Order Quantity for retailer

$$Q_i^r = \sqrt{2 * d_i^r * K_i^r / h_i^r}$$

Safety Stock for retailer

$$SS_i^r = s_i^r * SL_i^r$$

Stock of product i at time t at retailer

$$S_{it}^r = S_{i(t-1)}^r + SR_{it}^d + SB_{it}^d - F_{it}^r$$

Average Inventory at retailer for product i

$$I_i^r = \left[\sum_{t=0}^{t=n} S_{it}^r \right] / n$$

Average inventory at retailer for finished products at retailer

$$I^r = \left[\sum_{i=1}^{i=p} I_i^r \right] / p$$

Distributor

Economic Order Quantity for distributor

$$Q_i^d = \sqrt{2 * d_i^d * K_i^d / h_i^d}$$

Safety Stock at distributor

$$SS_i^d = s_i^d * SL_i^d$$

Stock of product i at time t at distributor

$$S_{it}^d = S_{i(t-1)}^d + SD_{it}^d - SB_{it}^d - F_{it}^d$$

Average Inventory at distributor for product i

$$I_i^d = \left[\sum_{t=0}^{t=n} S_{it}^d \right] \backslash n$$

Average inventory for product at the distributor

$$I^d = \left[\sum_{i=1}^{i=p} I_i^d \right] \backslash p$$

Distribution Requirement Planning (DRP)

Retailer

Maximum level of inventory for product i

$$M_i^r = Q_i^r + SS_i^r$$

Create planned orders or releases

$$\text{If } [S_{i(t-1)}^r + \sum_t^{t+LT^r} SR_{it}^d + SB_{it}^d - F_{it}^r] < 0$$

$$O_{it}^d = M_i^r - S_{it}^r$$

Distributor

Maximum level of inventory for product i

$$M_i^d = Q_i^d + SS_i^d$$

Create planned orders or releases

$$\text{If } [S_{i(t-1)}^d + \sum_t^{t+LT^d} SR_{it}^m + SB_{it}^m - F_{it}^d] < 0$$

$$O_{it}^d = M_i^r - S_{it}^d$$

Order point model

Retailer

Maximum level of inventory for product i

$$M_i^r = Q_i^r + RP_i^r$$

Reorder point

$$RP_i^r = SS_i^r + (d_i^r * LT_d)$$

Create purchase orders

$$\text{If } S_{i(t-1)}^r + \left[\sum_t^{t+LT^d} SR_{it}^d + SB_{it}^d \right] \leq RP_i^r$$

$$PO_{it}^r = M_i^r - S_{it}^r$$

Distributor

Maximum level of inventory for product i

$$M_i^d = Q_i^d + RP_i^d$$

Reorder point

$$RP_i^d = SS_i^d + (d_i^d * LT^d)$$

Create purchase orders for manufacturer

$$\text{If } S_{i(t-1)}^d + \left[\sum_t^{t+LT^d} SR_{it}^m + SB_{it}^m \right] \leq RP_i^d$$

$$PO_{it}^d = M_i^d - S_{it}^d$$

Performance measures:

Cost Model for retailer

$$C^r / h_i^r = \sum_{i=1}^{i=p} I_i^r + \sum_{i=1}^{i=p} (K_i^r / h_i^r * N_i^r) + \sum_{i=1}^{i=p} (C_{BO}^r / h_i^r * BO_i^r)$$

Cost Model for distributor

$$C^d / h_i^d = \sum_{i=1}^{i=p} I_i^d + \sum_{i=1}^{i=p} (K_i^d / h_i^d * N_i^d) + \sum_{i=1}^{i=p} (C_{iBO}^d / h_i^d * BO_i^d)$$

Fill rate

$$r^r = 1 - (N_{BO}^r / N^r)$$

Flexibility index (α)

$$\alpha = r^r / (C^r + C^d)$$

SUPPLY SIDE INVENTORY CONTROL POLICY

Index

t	Time period
i	Product index
j	Component index
n	Number of time period
p	Number of products
m	Number of components
Input	
variables	Manufacturer
x^m	Planning horizon for manufacturer
z^m	Frozen interval for manufacturer
K_j^m	Ordering cost for component j
h_j^m	Holding cost for component j
Q_j^m	Economic order quantity for component j
CQ_j^m	Container Quantity for component j
k_j^m	Number of kanbans for component j at manufacturer
M_j^m	Maximum level of inventory for component j at manufacturer
SS_j^m	Safety stock for component j
SL_j^m	Service level for component j
RP_j^m	Reorder point for component j at manufacturer
LT^m	lead time for transportation of components from supplier to manufacturer
S_{jt}^m	Stock of component j at time t at the manufacturer
S_{jt}	Stock at production line for component j at manufacturer
KO_{jt}^m	Order kanbans for component j at time t from manufacturer
PO_{jt}^m	Purchase orders of component j from manufacturer at time t
SR_{jt}^s	Scheduled receipts for component j from supplier at time t
SB_{jt}^s	Scheduled receipts for back orders j from supplier at time t

KR_{jt}^s	Receipt kanbans for component j at time t from supplier
KB_{jt}^s	Back order kanbans from supplier for component j at time t
BO_{jt}^m	Back orders for component j at time t
C_{jBO}^m	Penalty cost for back order per unit of component j
F_{it}^m	Forecasted demand for final product i at time t at the manufacturer
F_{jt}^m	Forecasted demand for component j at time t at the manufacturer
D_{it}^m	Actual demand for product i at time t at the manufacturer
D_{jt}^m	Actual demand for component j at manufacturer
d_{jt}^m	Mean demand for component j at manufacturer(forecast)
s_i^m	Standard deviation of demand for product i at manufacturer
s_j^m	Standard deviation of demand for component j at manufacturer
k_{jt}^m	Number of kanbans for component j at time t at manufacturer
u_{ij}	The indicator variable; equals 1 if part i is needed to make product j
v_{ij}	BOM factor; number of units of component j required to make one unit of product j
Inputs	
variables	
	Supplier
x^s	Planning period for supplier
z^s	Frozen interval for supplier
K_j^s	Setup cost for component j at supplier
h_j^s	Holding cost for component j at supplier
Q_j^s	Economic Production Quantity for component j at supplier
M_j^s	Maximum level of inventory for component j at supplier
S_{jt}^s	Stock for component j at supplier at time t
SS_j^s	Safety stock for component j at supplier
SL_j^s	Service level for component j at supplier
RP_j^s	Reorder point for component j at supplier

LT^s	Lead time for production of components for supplier
PO_{jt}^s	Production orders for component j at supplier
PR_{jt}^s	Production receipts for component j to supplier at time t
C_{jBO}^s	Penalty cost for back order per unit of component j
F_{jt}^s	Demand forecast for component j at supplier
D_{jt}^s	Actual demand for component j at supplier
d_{jt}^s	Mean demand for component j at supplier(forecast)
s_j^s	Standard deviation of demand for component j at supplier
Output variables	
N^m	Average quantity of orders from manufacturer per unit time period
N^s	Average quantity of production orders at supplier per unit time period
N_{BO}^m	Average quantity of back orders at manufacturer per unit time period
I_j^m	Average level of inventory for component j per unit time period
I^m	Average level of inventory at manufacturer per unit time period
I_j^s	Average level of inventory at supplier for component j per unit time period
I^s	Average level of inventory at supplier per unit time period
BO_j^m	Total number of back orders for component j per unit time period
BO_j^s	Total number of back orders for component j at supplier per unit time period
C^m	Total cost of maintaining inventory at manufacturer per unit time period
C^s	Total cost of maintaining inventory at supplier per unit time period

r^m	Fill rate at manufacturer
α	Flexibility index

Manufacturer

Forecasted demand for component j at manufacturer

$$F_{jt}^m = \sum_{i=1}^{i=p} (u_{ij} * v_{ij} * F_{it}^m)$$

Actual demand for component j at manufacturer

$$D_{jt}^m = \sum_{i=1}^{i=p} (u_{ij} * v_{ij} * D_{it})$$

Standard deviation of demand for component j at manufacturer

$$s_j^m = \sqrt{\left[\sum_{i=1}^{i=p} v_{ij} * u_{ij} * (s_i^m)^2 \right]}$$

Safety Stock for component j at manufacturer

$$SS_j^m = (s_j^m * SL_j^m)$$

Economic Order Quantity (EOQ) for manufacturer

$$Q_j^m = \sqrt{(2 * K_j^m * d_j^m / H_j^m)}$$

Average Inventory at of component j at manufacturer

$$I_j^m = \left[\sum_{t=0}^{t=n} S_{jt}^m \right] \setminus n$$

Average inventory at supplier

$$I^m = \left[\sum_{j=1}^{j=m} I_j^m \right] \setminus m$$

Supplier

Economic Production Quantity (EPQ) for Supplier

$$Q_j^s = \sqrt{(2 * K_j^s * d_j^s / H_j^s)}$$

Safety stock for component j at supplier

$$SS_j^s = (s_j^s * SL_j^s)$$

Average Inventory at supplier for component j

$$I_j^s = \left[\sum_{t=0}^{t=n} S_{jt}^s \right] \setminus n$$

Average inventory at supplier

$$I^s = \left[\sum_{j=1}^{j=m} I_j^s \right] / m$$

Materials Requirement Planning

Manufacturer

Maximum level of inventory for component j

$$M_j^m = Q_j^m + SS_j^m$$

Stock of component i at time t

$$S_{jt}^m = S_{j(t-1)}^m + SR_{jt}^s + SB_{jt}^s - D_{jt}^m$$

Create planned orders or releases

$$\text{If } [S_{j(t-1)}^m + \sum_t^{t+LT^m} (SB_{jt}^s + SR_{jt}^s - F_{jt}^m)] < 0$$

$$PO_{jt}^m = M_j^m - S_{jt}^m$$

Supplier

Maximum level of inventory for component j

$$M_j^s = Q_j^s + RP_j^s$$

Reorder point

$$RP_j^s = SS_j^s + (d_j^s * LT^s)$$

Stock of component j at time t

$$S_{jt}^s = S_{j(t-1)}^s + PR_{jt}^s - PO_{jt}^m$$

Create production orders

$$\text{If } S_{j(t-1)}^s + \left[\sum_t^{t+LT^s} PR_{jt}^s \right] - PO_{jt}^m \leq RP_j^s$$

$$PO_{jt}^s = M_j^s - S_{jt}^s$$

Order point model

Manufacturer

Maximum level of inventory for component j

$$M_j^m = Q_j^m + RP_j^m$$

Reorder point for component j

$$RP_j^m = SS_j^m + (d_j^m * LT^d)$$

Stock of component j at time t

$$S_{jt}^m = S_{j(t-1)}^m + SR_{jt}^s + SB_{jt}^s - D_{jt}^m$$

Create purchase orders

$$\text{If } S_{j(t-1)}^m + \sum_t^{t+L_j^m} (SB_{jt}^s + SR_{jt}^s) \leq RP_j^m$$

$$PO_{jt}^m = M_j^m - S_{jt}^m$$

Supplier

Maximum level of inventory for component j

$$M_j^s = Q_j^s + RP_j^s$$

Reorder point

$$RP_j^s = SS_j^s + (d_j^s * LT^s)$$

Stock of component j at time t

$$S_{jt}^s = S_{j(t-1)}^s + PR_{jt}^s - PO_{jt}^m$$

Create production orders

$$\text{If } S_{j(t-1)}^s + \left[\sum_t^{t+L_j^s} PR_{jt}^s \right] - PO_{jt}^m \leq RP_j^s$$

$$PO_{jt}^s = M_j^s - S_{jt}^s$$

Just in Time

Manufacturer

Number of Kanbans for component j

$$k_j^m = (d_j^m * (LT^m) + SS_j^m) / CQ_j^m$$

Inventory at production line

$$S_{jt}^m = S_{j(t-1)}^m - D_{jt}^m$$

Number of Kanbans for component j at time t

$$k_{jt}^m = k_{j(t-1)}^m + KR_{jt}^s - |\text{Approx.}(S_{jt}^m / CQ_j^m)|$$

Create order Kanbans

$$\text{If } k_{j(t-1)}^m + \left[\sum_t^{t+L_j^m} (KR_{jt}^s + KB_{jt}^s) \right] - |\text{Approx.}(S_{jt}^m / CQ_j^m)| < k_j^m$$

$$KO_{jt}^m = k_j^m - \left\{ k_{j(t-1)}^m + \left[\sum_t^{t+L_j^m} (KR_{jt}^s + KB_{jt}^s) \right] - |\text{Approx.}(S_{jt}^m / CQ_j^m)| \right\}$$

Supplier

Maximum level of inventory for component j

$$M_j^s = Q_j^s + RP_j^s$$

Reorder point

$$RP_j^s = SS_j^s + (d_j^s * LT^s)$$

Stock of component j at time t

$$S_{jt}^s = S_{j(t-1)}^s + PR_{jt}^s - PO_{jt}^m$$

Create production orders

$$\text{If } S_{j(t-1)}^s + \left[\sum_t^{t+LT^s} PR_{jt}^s \right] - PO_{jt}^m \leq RP_j^s$$

$$PO_{jt}^s = M_j^s - S_j^s$$

Performance metrics

Cost Model for manufacturer

$$C^m / h_j = \sum_{j=1}^{j=m} I_j^m + \sum_{j=1}^{j=m} ((K_j^m / h_j) * N_j^m) + \sum_{j=1}^{j=m} ((C_{jBO}^m / h_j) * BO_{jt}^m)$$

Cost Model for supplier

$$C^s / h_j = \sum_{j=1}^{j=m} I_j^s + \sum_{j=1}^{j=m} ((K_j^s / h_j) * N_j^m) + \sum_{j=1}^{j=m} ((C_{jBO}^s / h_j) * BO_{jt}^s)$$

Fill rate (r)

$$r^m = 1 - (N_{BO}^m / N^m)$$

Flexibility index (α)

$$\alpha = r^m / ((C^m + C^s))$$

DECOUPLING POINT

Index

t	Time period
i	Product index
j	Component index
k	WIP material index
n	Number of time period
p	Number of products
m	Number of components

Input

variables

	Distributor
x^d	Planning period for distributor
M_i^d	Maximum level of inventory for product i at distributor
SS_i^d	Safety stock at distributor for product i
LT^d	Lead time for replenishing finished goods stock at the distributor warehouse
LT^a	Lead time for transportation of goods from assembler to distributor
LT^m	Lead time for assembly of products
LT^s	Lead time for manufacturing products
	Lead time for transportation of goods from supplier to manufacturer
S_{it}^d	Stock of product i at distributor at time t
SR_{it}^a	Scheduled receipts for product i from assembler at time t
D_{it}^d	Actual demand for product i at time t at the distributor
d_i^d	Mean demand at distributor for product i a time t (forecast)
D_{jt}^m	Actual demand for raw material j at manufacturer at time t
C_{iBO}^d	Penalty cost per unit back order of product i

PO_{it}^d	Production orders by distributor for product i a time t
Q_i^d	Economic Order Quantity for product i at time t at the distributor
RP_i^d	Reorder point for product i at the distributor
s_i^d	Standard deviation of demand for product i the distributor
SL_i^d	Service level of product i at the distributor
BO_{it}^d	Back order quantity for product i at the distributor at time t
K_i^d	Ordering cost for product i at the distributor
h_i^d	Holding cost for product i at the distributor
K_{im}	Processing cost for manufacturing per unit of product i
K_{ika}	Holding cost for raw materials per unit per time period at manufacturer
h_j^m	
K_j^m	Ordering cost for raw materials per unit per time period
v_{ij}	Bill of Material index; quantity of raw material j required to produce one unit of product i
Input variables	Assembler
x^a	Planning period for assembler
M_k^a	Maximum level of inventory for WIP material k at assembler
SS_k^a	Safety stock of WIP material k at assembler
S_{kt}^a	Stock of WIP material k at distributor at time t at assembler
SR_{kt}^m	Scheduled receipts from manufacturer for WIP material k at time t
d_i^a	Mean demand for product i at the assembler(forecast)
D_{kt}^a	Actual demand for WIP material k at time t at assembler
d_k^a	Average demand for WIP material k at assembler(forecast)
PO_{kt}^a	Purchase orders for WIP material k at time t
Q_k^a	Economic Production Quantity of WIP material k of at time t at assembler
RP_k^a	Reorder point of raw material k at time t at assembler
s_i^a	Standard deviation of demand for product i at assembler

s_k^a	Standard deviation of demand for WIP material k at assembler
SL_k^a	Service level of WIP inventory k of at assembler
V_{ik}	Bill of Material index
BO_{it}^a	Back orders of WIP inventory i at assembler at time t
K_{ik}^a	Set up cost of WIP material k
h_k^a	Inventory holding cost of WIP material k
C_{iBO}^a	Penalty cost for back order of product
Input variables	Manufacturer
x^m	Planning period for manufacturer
M_j^m	Maximum stock of raw material j at the manufacturer
LT^m	Lead time for manufacture of WIP material
S_{jt}^m	Stock of raw material j at the manufacturer at time t
SR_{jt}^s	Scheduled receipts by supplier for raw material j
D_{it}^m	Actual demand for product i at time t at the manufacturer
D_{jt}^m	Actual demand for raw material j at time t at the manufacturer
d_i^m	Mean demand for product i at time t (forecast)
d_j^m	Mean demand for raw material j at time t (forecast)
C_{iBO}^m	Penalty cost per back order unit of product i
PO_{jt}^m	Purchase orders to supplier for raw material j at time t
Q_j^m	Economic Order Quantity for raw material j
SS_j^m	Safety stock for raw material j at manufacturer
RP_j^m	Reorder point of raw material j at manufacturer
s_i^m	Standard deviation of demand for product i at manufacturer
s_j^m	Standard deviation of demand for raw material j at manufacturer
SL_j^m	Service level for raw material j at the manufacturer
BO_{it}^m	Back order quantity of product i at manufacturer at time t
K_j^m	Ordering costs for raw material j at manufacturer
h_j^m	Holding costs for raw material j at manufacturer

Output
variables

BO_i^d	Average back order quantity for product i at distributor per unit time period
N^d	Average order quantity placed by distributor per unit time period
I_i^d	Average inventory for product i at the distributor per unit time period
I^d	Average inventory of finished products at distributor per unit time period
C^d	Total cost of maintaining inventory at distributor per unit time period
BO_i^a	Average back order quantity of product i at assembler per unit time
N^a	Average number of orders placed by the assembler per unit time
h_k^a	Holding cost for raw material k at assembler
I_k^a	Average inventory of raw material k at the assembler per unit time
C^a	Total cost of maintaining the inventory by assembler per unit time
BO_i^m	Total number of back orders for product i at manufacturer per unit time
N^m	Total number of orders placed by manufacturer per unit time
I_j^m	Average inventory of raw material j at manufacturer per unit time
I^m	Average inventory of raw materials at manufacturer per unit time
C^m	Total cost of maintaining inventory at manufacturer per unit time
α	Flexibility index

Make-to-stock supply chain

Distributor

Economic Order Quantity

$$Q_i^d = \sqrt{2 * d_i^d * K_i^d / h_i^d}$$

Safety Stock

$$SS_i^d = s_i^d * SL_i^d$$

Maximum level of inventory for product i

$$M_i^d = Q_i^d + RP_i^d$$

Reorder point

$$RP_i^d = SS_i^d + (d_i^d * LT)$$

Stock of product j at time t

$$S_{it}^d = S_{i(t-1)}^d + SR_{it}^a - D_{it}^d$$

Average Inventory at distributor for product i

$$I_i^d = \left[\sum_{t=0}^{t=n} S_{it}^d \right] \backslash n$$

Average inventory at distributor

$$I^d = \left[\sum_{i=1}^{i=p} I_i^d \right] \backslash p$$

Create production orders to manufacturer

$$\text{If } S_{i(t-1)}^d + \sum_i^{t+LT} SR_{it}^a - D_{it}^d \leq RP_i^d$$

$$PO_{it}^d = M_i^d - S_{it}^d$$

Manufacturer

Demand for raw material j

$$D_{jt}^m = \sum_{i=1}^{i=p} (v_{ij} * PO_{it}^d)$$

Create purchase orders to suppliers for component j

$$PO_{jt}^m = D_{jt}^m$$

Cost Model for finished goods

$$C^d / h_i^d = \sum_{i=1}^{i=p} I_j^d + \sum_{i=1}^{i=p} ((K_i^d / h_i^d) * N_j^d) + \sum_{i=1}^{i=p} ((C_{iBO}^d / h_i^d) * BO_i^d)$$

Cost model for WIP inventory

$$C^{WIP} / h_i^d = \sum_{k=1}^{k=w} ((PO_{it}^d * v_{ik} * LT^m) * (h_k^m / h_i^d)) + \sum_{k=1}^{k=w} (PO_{it}^d * v_{ik} * LT^a) * (h_k^a / h_i^d)$$

Cost model for raw materials

$$C^m / h_i^m = \sum_{j=1}^{j=m} (h_j^m / h_i^d) * I_j^m + \sum_{i=1}^{i=p} ((K_j^m / h_i^d) * N_j^m)$$

Total cost model

$$C = C^d / h_i^d + C^{WIP} / h_i^d + C^m / h_i^m$$

Assemble- to-order Supply Chain

Assembler

Economic Order Quantity

$$Q_k^a = \sqrt{(2 * d_k^a * K_k^a / h_k^a)}$$

Maximum level of inventory for work in process inventory k

$$M_k^a = Q_k^a + RP_k^a$$

Safety Stock

$$SS_k^a = (s_k^a * SL_k^a)$$

$$s_k^a = \sqrt{\left[\sum_{i=1}^{i=p} v_{ik} * (s_i^a)^2 \right]}$$

Demand for WIP inventory k

$$D_{kt} = \sum_{i=1}^{i=p} D_{it}^a$$

Reorder point

$$RP_k^a = SS_k^a + (d_k^a * (LT^m + LT^s))$$

Stock of WIP material k at time t

$$S_{kt}^a = S_{kt}^a + SR_{kt}^m - D_{kt}^a$$

Average inventory at distributor for raw material k

$$I_k^a = \left[\sum_{t=0}^{t=n} S_{kt}^a \right] \setminus n$$

Create production orders to manufacturer

$$\text{If } S_{kt}^a + \left[\sum_t^{t+LT} SR_{kt}^m \right] - D_{kt}^a \leq RP_k^a$$

$$PO_{kt}^a = M_k^a - S_{kt}^a$$

Manufacturer

Demand for raw material j

$$D_{jt}^m = \sum_{k=1}^{k=w} (v_{kj} * PO_{kt}^a)$$

Create purchase orders to suppliers for raw material j

$$PO_{jt}^m = D_{jt}^m$$

Cost model for WIP inventory

$$C^{WIP} / h_i^d = \sum_{k=1}^{k=w} ((PO_{it}^d * v_{ik} * LT^m) * (h_k^m / h_i^d)) + \sum_{k=1}^{k=w} (PO_{it}^d * v_{ik} * LT^a) * (h_k^a / h_i^d)$$

Cost model for buffer WIP inventory

$$C^a / h_i^d = \sum_{k=1}^{k=w} (h_j^a / h_j^d) * I_k^a + \sum_{k=1}^{k=w} ((K_k^a / h_i^d) * N_k^a)$$

Cost model for raw materials

$$C^m / h_i^m = \sum_{j=1}^{j=m} (h_j^m / h_j^d) * I_j^m + \sum_{j=1}^{j=m} ((K_j^m / h_i^d) * N_j^m)$$

Total cost model

$$C = C^a / h_i^d + C^{WIP} / h_i^d + C^m / h_i^m + (d_i^m * K_i^a)$$

Make-to-order Supply chain

Manufacturer

Economic Order Quantity of raw material j

$$Q_j^m = \sqrt{2 * d_j^m * K_j^m / h_j^m}$$

Demand for raw material j

$$D_{jt}^m = \sum_{i=1}^{i=p} (v_{ij} * D_{it}^m)$$

Maximum level of inventory for raw material j

$$M_j^m = Q_j^m + RP_j^m$$

Safety Stock for raw material j

$$SS_j^m = (s_j^m * SL_j^m)$$

$$s_j^m = \sqrt{\left[\sum_{i=1}^{i=p} v_{ij} * (s_j^m)^2 \right]}$$

Reorder point for raw material j

$$RP_j^m = SS_j^m + (d_j^m * LT^s)$$

Stock of raw material j at time t

$$S_{jt}^m = S_{j(t-1)}^m + SR_{jt}^s - D_{jt}^m$$

Average Inventory at distributor for WIP material

$$I_k^a = \left[\sum_{t=0}^{t=n} S_{kt}^a \right] / n$$

Create purchase orders

$$\text{If } S_{jt}^m + \left[\sum_t^{t+LT} SR_{jt}^s \right] \leq RP_j^m$$

$$PO_{jt}^m = M_j^m - S_j^m$$

Cost model for WIP inventory

$$C^{WIP} / h_i^d = \sum_{k=1}^{k=w} ((PO_{it}^d * v_{ik} * LT^m) * (h_k^m / h_i^d)) + \sum_{k=1}^{k=w} (PO_{it}^d * v_{ik} * LT^a) * (h_k^a / h_i^d)$$

Cost model for raw materials

$$C^m / h_i^m = \sum_{j=1}^{j=m} (h_j^m / h_i^d) * I_j^m + \sum_{j=1}^{j=m} ((K_j^m / h_i^d) * N_j^m)$$

Total cost model

$$C = + C^{WIP} / h_i^d + C^m / h_i^m + (d_i^m * (K_i^a + K_i^m))$$

Performance metrics:

Fill rate

$$r^d = 1 - (N_{BO}^d / N^d)$$

Flexibility index (α)

$$\alpha = r^f / C$$

APPENDIX B
DESIGN OF EXPERIMENTS

This appendix consists of tables, which show the inputs that have been designed to determine new product flexibility, product mix flexibility, demand flexibility, and delivery flexibility respectively.

Table 1 Experiment to determine new product flexibility

Product life cycle	1 year		2 years		3 years	
Time period	Forecasted Demand	Real Demand	Forecasted Demand	Real Demand	Forecasted Demand	Real Demand
1	N(100,10)	N(100,100)	N(50,5)	N(50, 30)	N(50, 5)	N(50, 15)
2	N(150, 15)	N(150,150)	N (70,7)	N(70,42)	N(70,7)	N(70,21)
3	N(200,20)	N(200,180)	N(100,10)	N(100, 50)	N(100, 10)	N(100, 50)
4	N(500,50)	N(500,250)	N(110,11)	N(110, 55)	N(110, 11)	N(110, 55)
5	N(500,50)	N(500,250)	N(120,12)	N(120, 60)	N(120, 12)	N(120, 60)
6	N(200,20)	N(200, 80)	N(200,20)	N(200,80)	N(150,15)	N(150,60)
7	N(150,15)	N(150,60)	N(500,50)	N(500, 100)	N(160,16)	N(160,48)
8	N(100,10)	N(100,20)	N(500,50)	N(500, 100)	N(200,20)	N(200,60)
9	N(50, 5)	N(50,10)	N(500,50)	N(500, 100)	N(250,25)	N(250,75)
10			N(500,50)	N(500, 100)	N(500,50)	N(500,100)
11			N(500,50)	N(500, 100)	N(500,50)	N(500,100)
12			N(450,45)	N(450, 90)	N(500,50)	N(500,100)
13			N(200,20)	N(200, 40)	N(500,50)	N(500,100)
14			N(120,12)	N(120, 24)	N(500,50)	N(500,100)
15			N(110,11)	N(110,22)	N(500,50)	N(500,100)
16			N(90,9)	N(90, 18)	N(500,50)	N(500,100)
17			N(70,7)	N(70,14)	N(500,50)	N(500,100)
18			N(50,5)	N(50,10)	N(500,50)	N(500,100)
19					N(300, 30)	N(300, 15)
20					N(200, 20)	N(200, 10)
21					N(120, 12)	N(120, 6)
22					N(110,11)	N(110,5)
23					N(100,10)	N(100,5)
24					N(90,9)	N(90,4)
25					N(80,8)	N(80,4)

26					N(70,7)	N(70,3)
27					N(50,5)	N(50,2)

Table 2 Experiment input to determine product mix flexibility

	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5
Volume 1	N(250,25)	N(300,30)	N(350,35)	N(150,15)	N(100,10)
Mean demand =500	N(100,10)	N(100,10)	N(50,5)	N(100,10)	N(100,10)
Number of products = 5	N(50,5)	N(50,5)	N(25,3)	N(75,8)	N(100,10)
	N(25,3)	N(25,3)	N(25,3)	N(100,10)	N(100,10)
	N(75,8)	N(25,3)	N(50,5)	N(75,8)	N(100,10)
	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5
Volume 2	N(300,30)	N(150,15)	N(500, 50)	N(150,15)	N(100,10)
Mean demand =1000	N(150,15)	N(175,18)	N(15,2)	N(150,15)	N(100,10)
Number of products = 10	N(75,8)	N(250,25)	N(25,3)	N(100,10)	N(100,10)
	N(25,3)	N(75,8)	N(50,5)	N(125,13)	N(100,10)
	N(100,10)	N(25,3)	N(75,8)	N(100,10)	N(100,10)
	N(175,18)	N(50,5)	N(100,10)	N(75,8)	N(100,10)
	N(50,5)	N(125,13)	N(125,13)	N(125,13)	N(100,10)
	N(25,3)	N(50,5)	N(10,10)	N(75,8)	N(100,10)
	N(50,5)	N(85,8)	N(50,5)	N(50,5)	N(100,10)
	N(50,5)	N(15,2)	N(50,5)	N(50,5)	N(100,10)
	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5
Volume 3	N(400,40)	N(200, 20)	N(125,13)	N(500,50)	N(100,10)
Mean demand =1500	N(150,15)	N(175, 18)	N(100,10)	N(75,8)	N(100,10)
Number of products =15	N(75,8)	N(250,25)	N(75,8)	N(100,10)	N(100,10)
	N(25,3)	N(100,10)	N(125,13)	N(125,13)	N(100,10)
	N(100,10)	N(25,3)	N(125,13)	N(100,10)	N(100,10)
	N(175,18)	N(50,5)	N(100,10)	N(75,8)	N(100,10)
	N(75,8)	N(125,13)	N(125,13)	N(125,13)	N(100,10)

APPENDIX C
SIMULATION ANALYSIS RESULTS

This appendix consists of simulation output analysis graphs. The simulation output graphs which depict the confidence intervals of the difference between the performances the alternatives, that are plotted to compare the performance of alternatives for, 1) Demand side inventory control policy, 2) Supply side inventory control policy, and 3) Decoupling point respectively.

Demand side inventory control policy

1. Demand flexibility

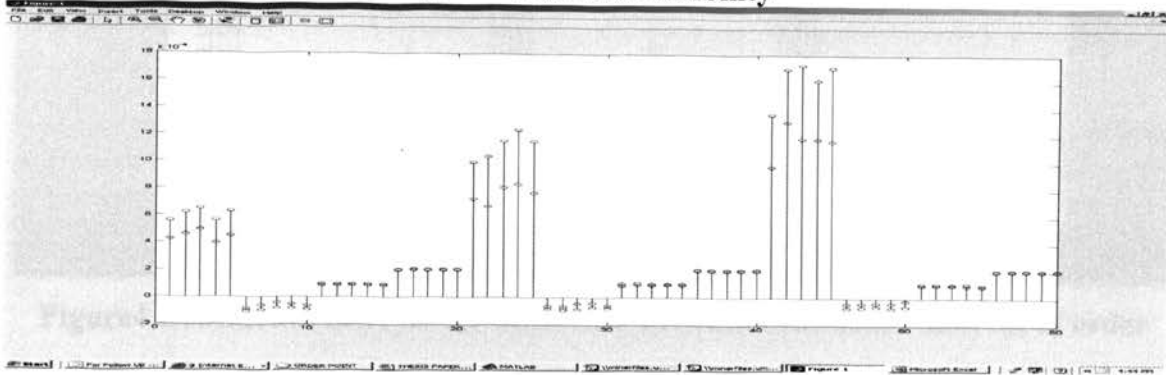


Figure1 Confidence interval for difference between confidence interval of order point and DRP (volume 1)

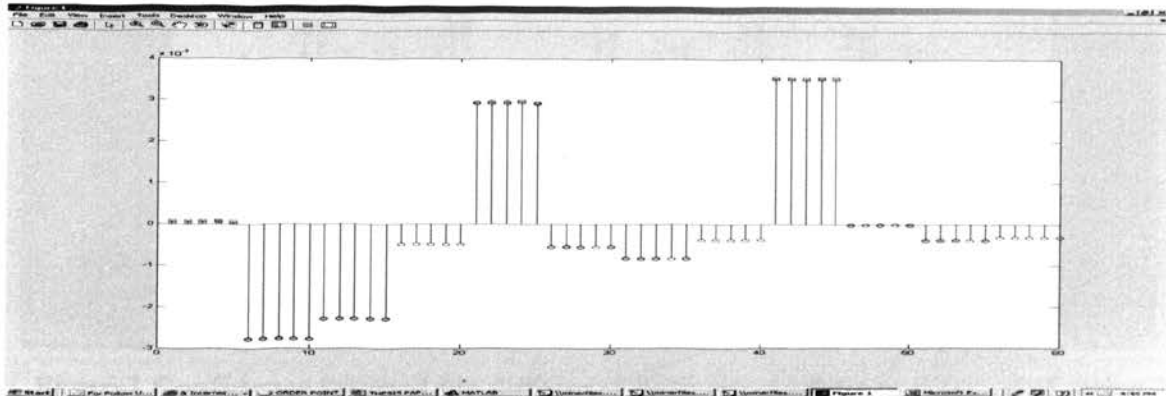


Figure2 Confidence interval for difference between confidence interval of order point and DRP (volume 2)

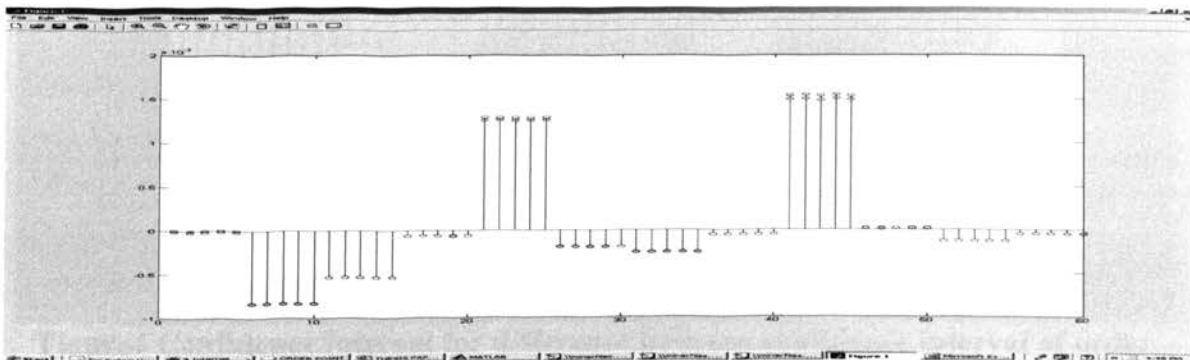


Figure3 Confidence interval for difference between confidence interval of order point and DRP (volume 3)

2. Delivery flexibility

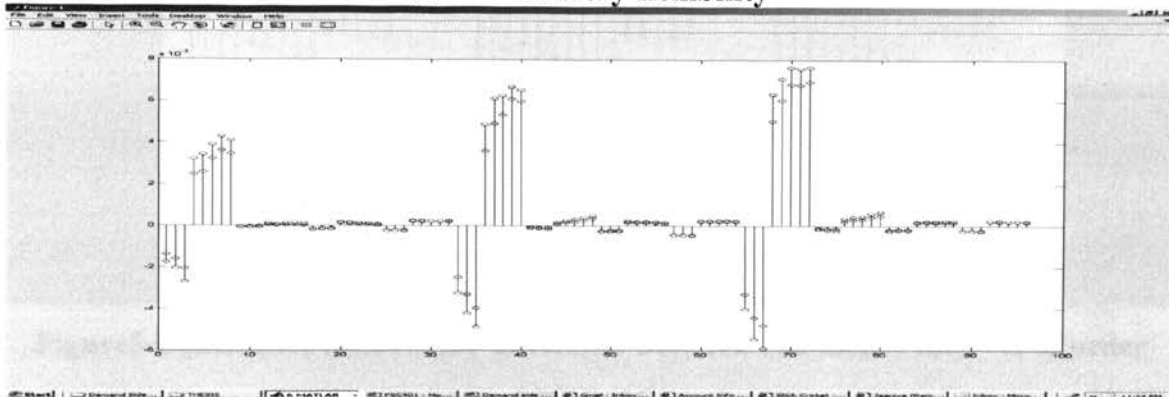


Figure4 Confidence interval for difference between confidence interval of order point and DRP

3. Product mix flexibility

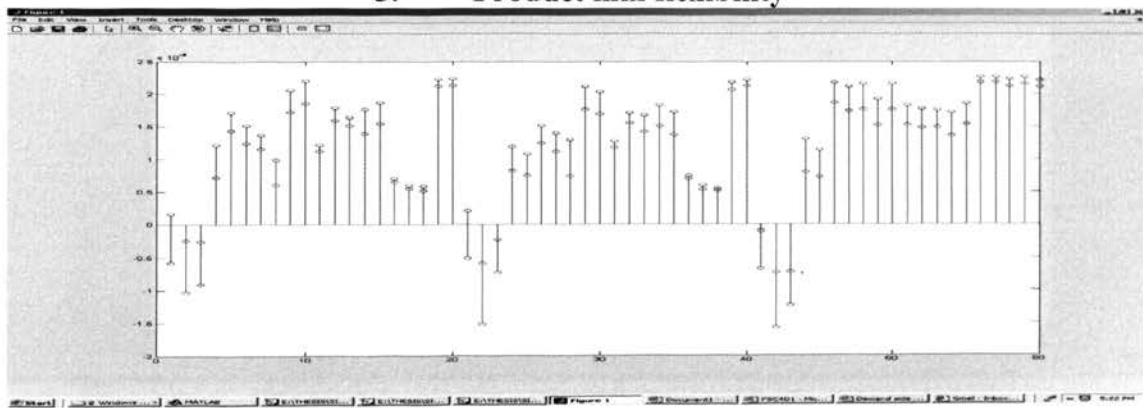


Figure3 Confidence interval for difference between confidence interval of order point and DRP (5 products)

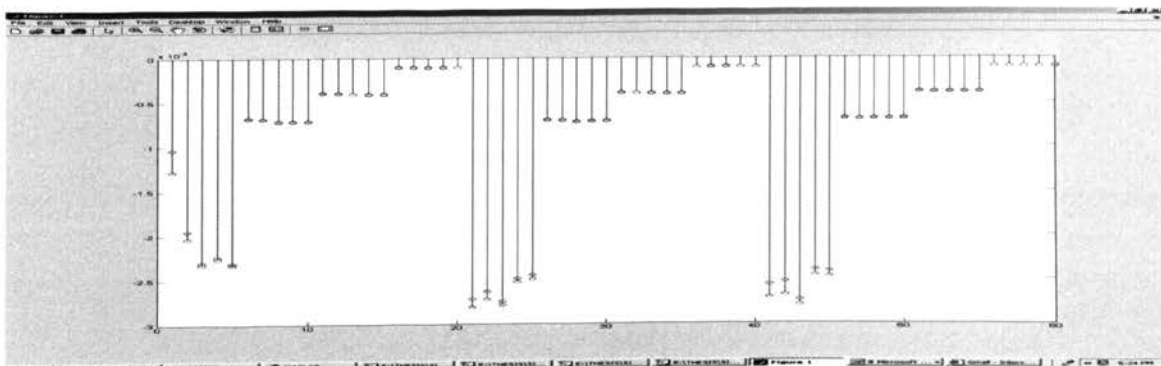


Figure4 Confidence interval for difference between confidence interval of order point and DRP (10 products)

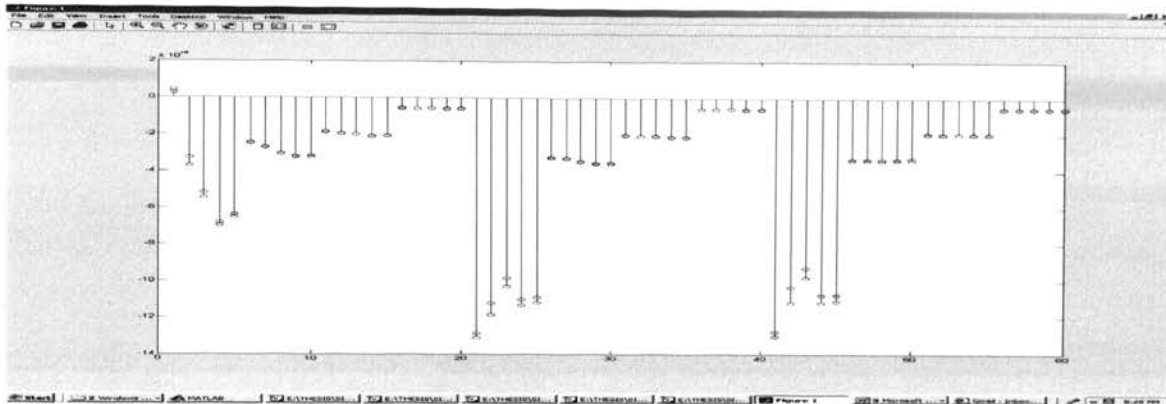


Figure5 Confidence interval for difference between confidence interval of order point and DRP (15 products)

4. New product flexibility

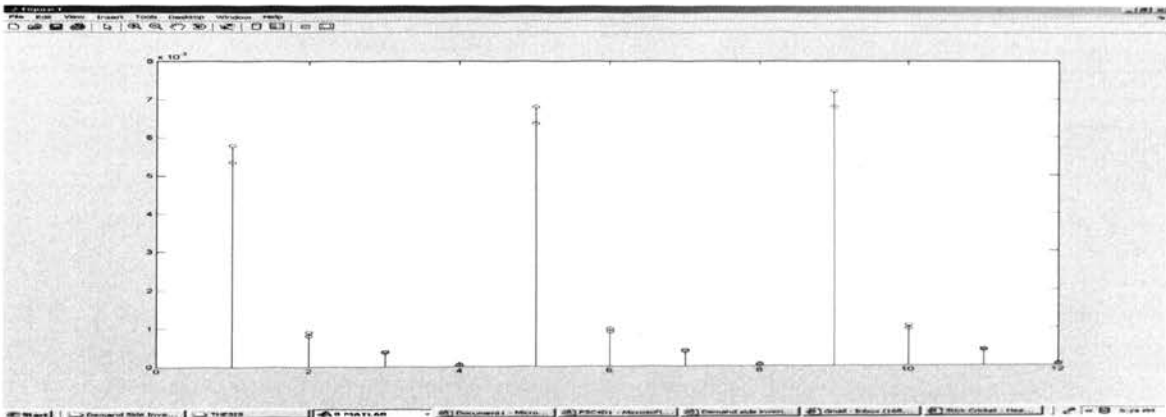


Figure6 Confidence interval for difference between confidence interval of order point and DRP (1 year)

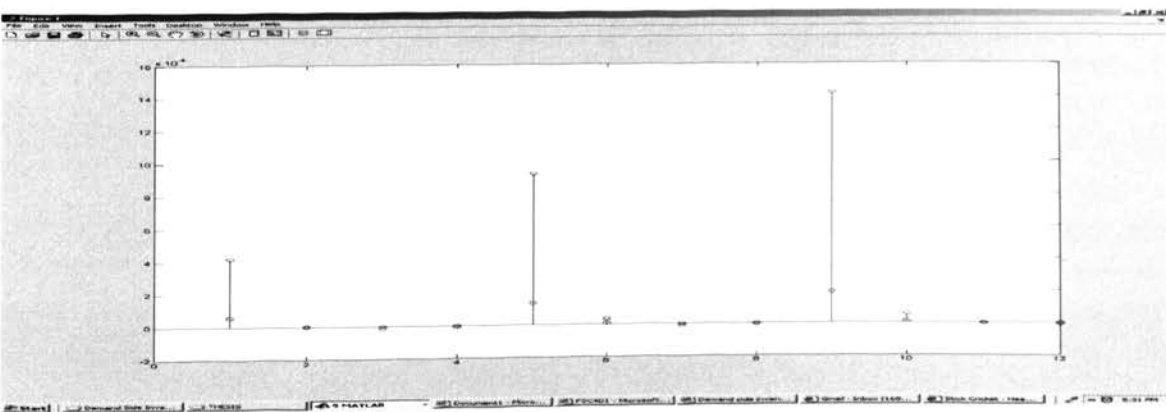


Figure7 Confidence interval for difference between confidence interval of order point and DRP (2 year)

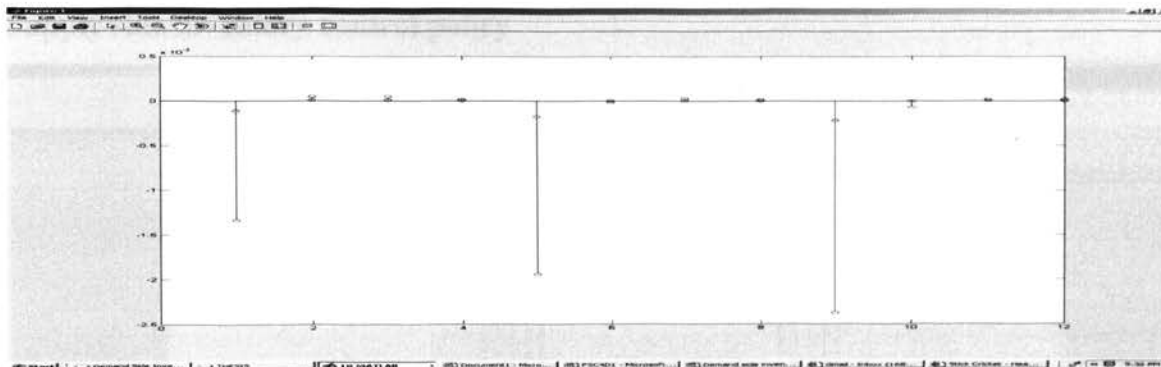


Figure8 Confidence interval for difference between confidence interval of order point and DRP (3 year)

Supply side inventory control policy

1. Demand Flexibility

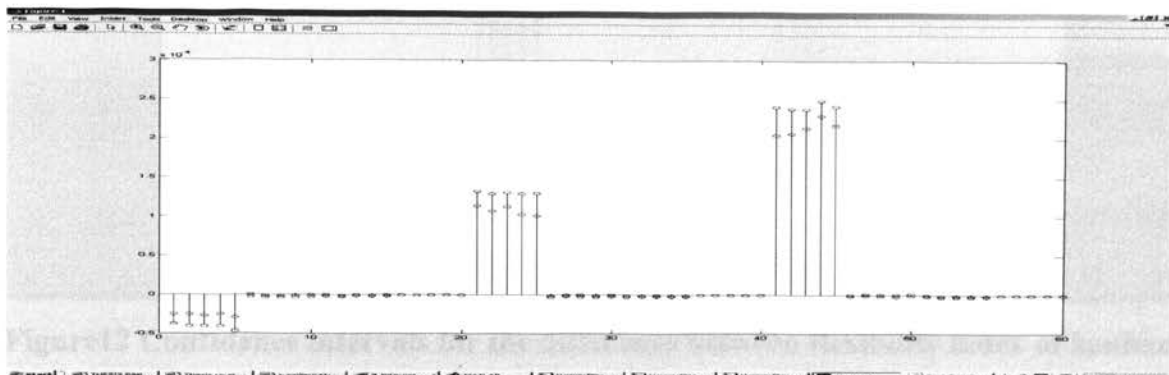


Figure9 Confidence intervals for the difference between flexibility index of kanban and MRP (volume 1)

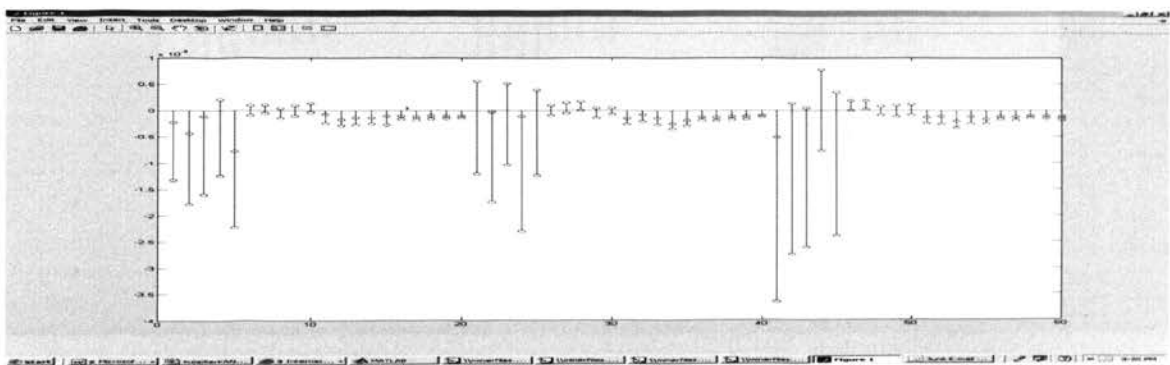


Figure10 Confidence intervals for the difference between flexibility index of kanban and order point (volume 1)

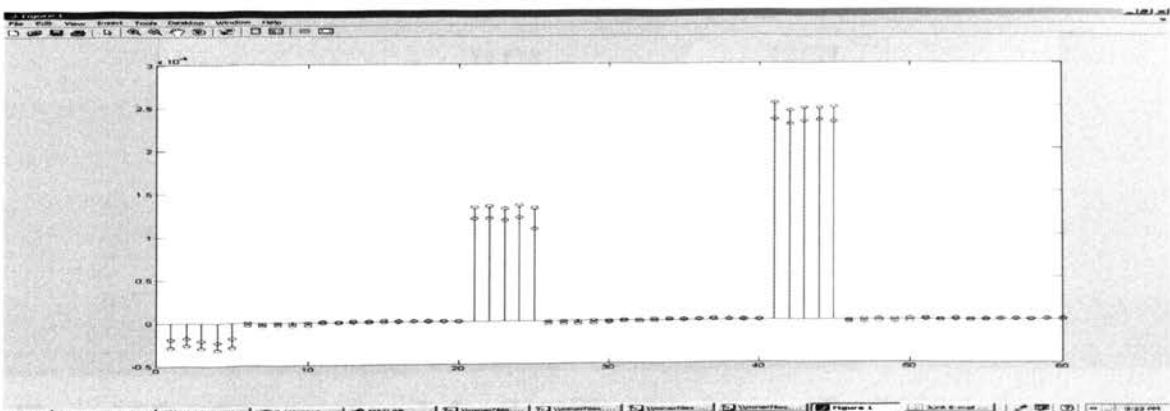


Figure11 Confidence intervals for the difference between flexibility index of order point and MRP (volume 1)

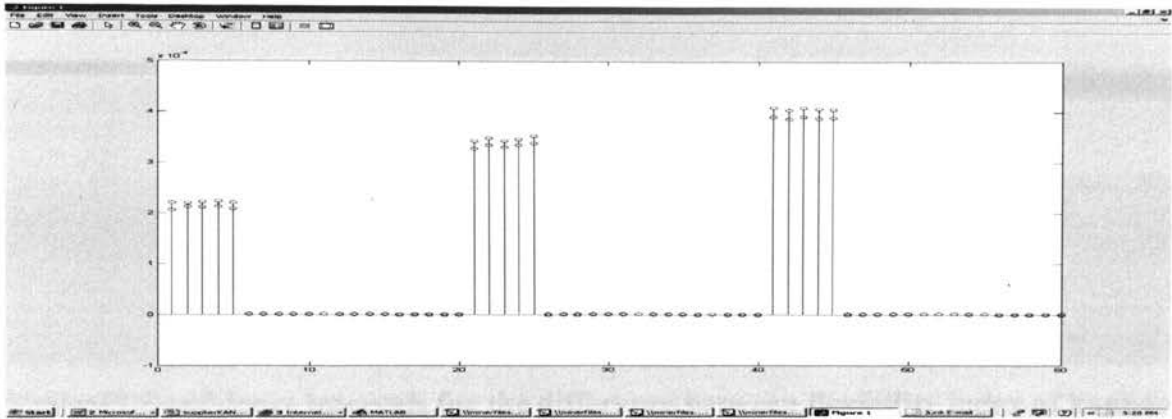


Figure12 Confidence intervals for the difference between flexibility index of kanban and MRP (volume 2)

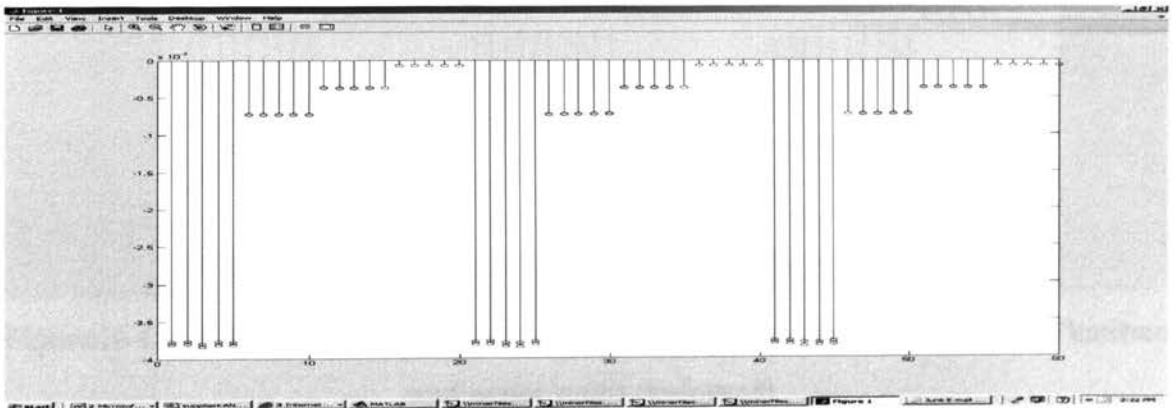


Figure13 Confidence intervals for the difference between flexibility index of kanban and order point (volume 2)

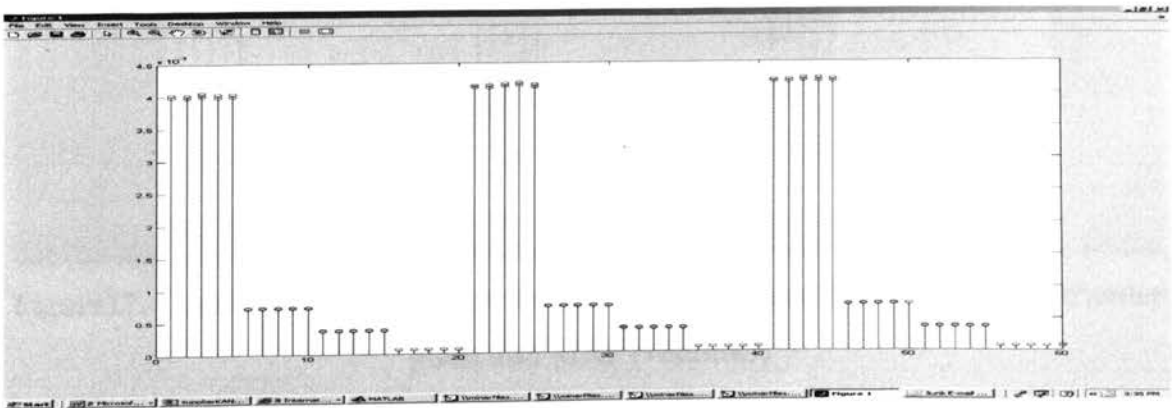


Figure14 Confidence intervals for the difference between flexibility index of order point and MRP (volume 2)

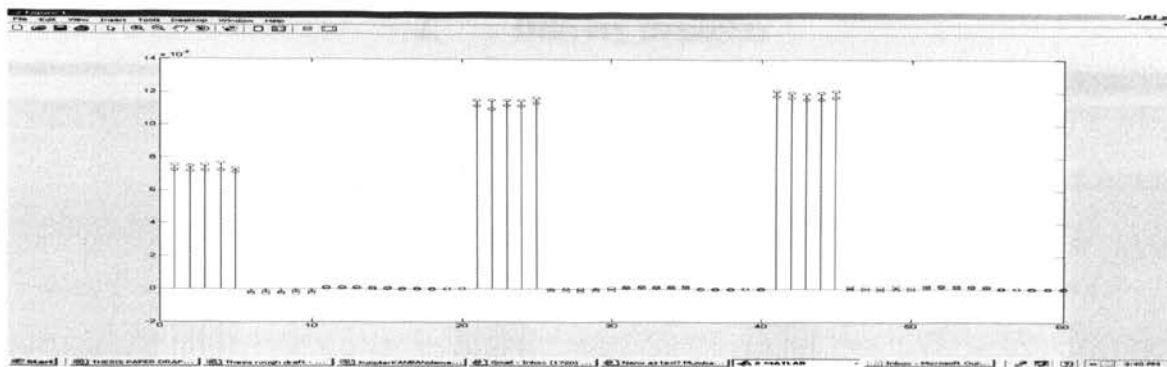


Figure15 Confidence intervals for the difference between flexibility index of kanban and MRP (volume 3)

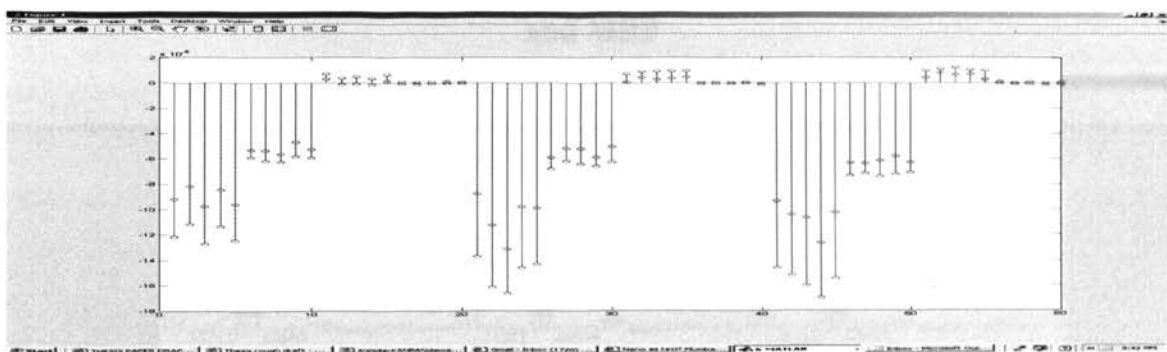


Figure16 Confidence intervals for the difference between flexibility index of kanban and order point (volume3)

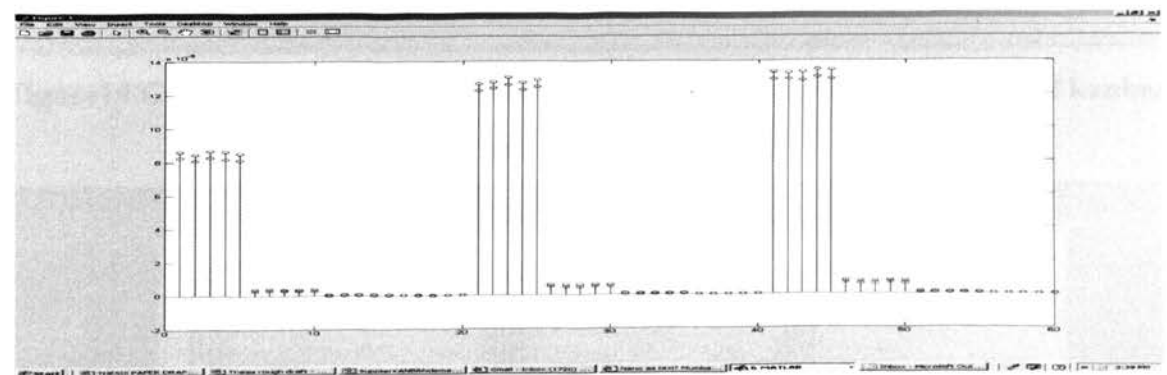


Figure17. Confidence intervals for the difference between flexibility index of order point and MRP (volume3)

2. Delivery flexibility

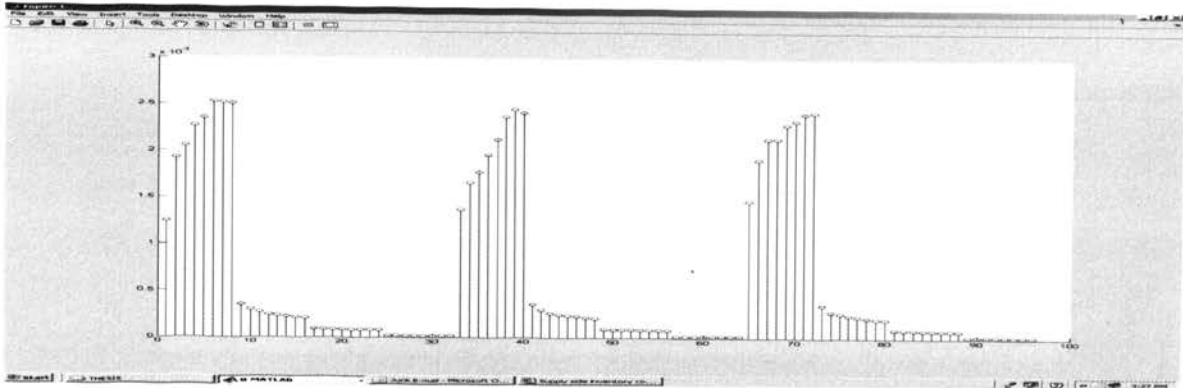


Figure18 Confidence intervals for the difference between flexibility index of kanban and MRP

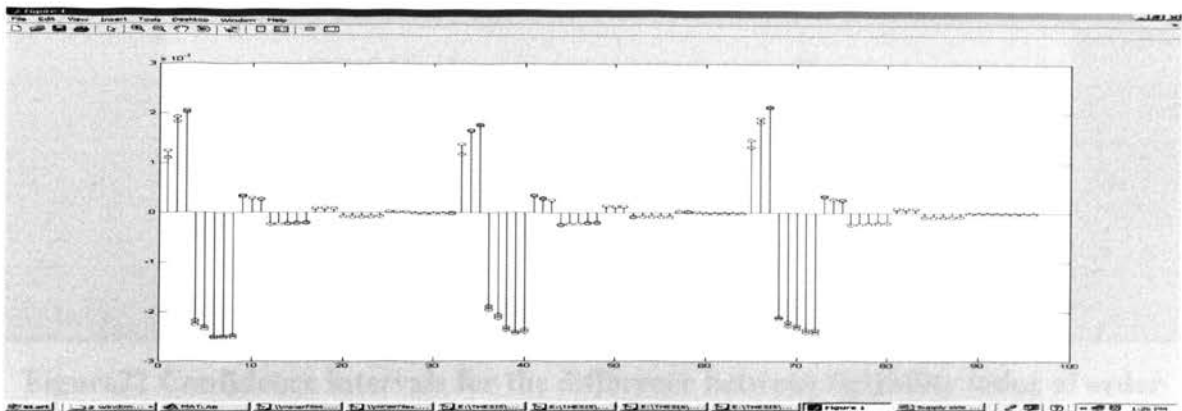


Figure19 Confidence intervals for the difference between flexibility index of kanban and order point.

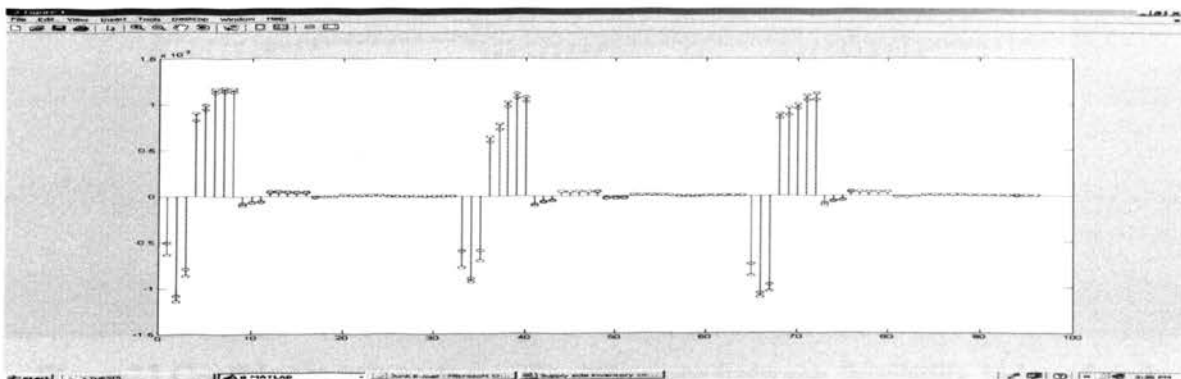


Figure20 Confidence intervals for the difference between flexibility index of order point and MRP

3. Product mix flexibility

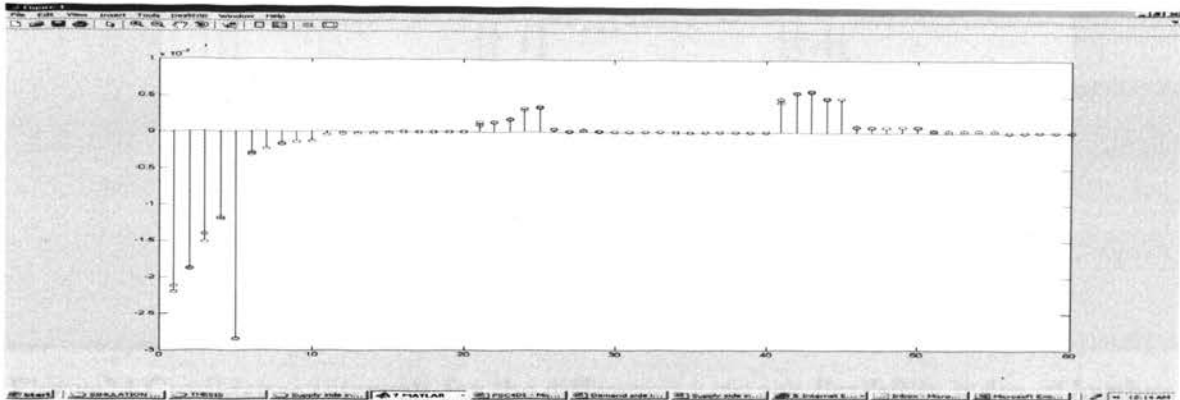


Figure21 Confidence intervals for the difference between flexibility index of kanban and MRP (5 products)

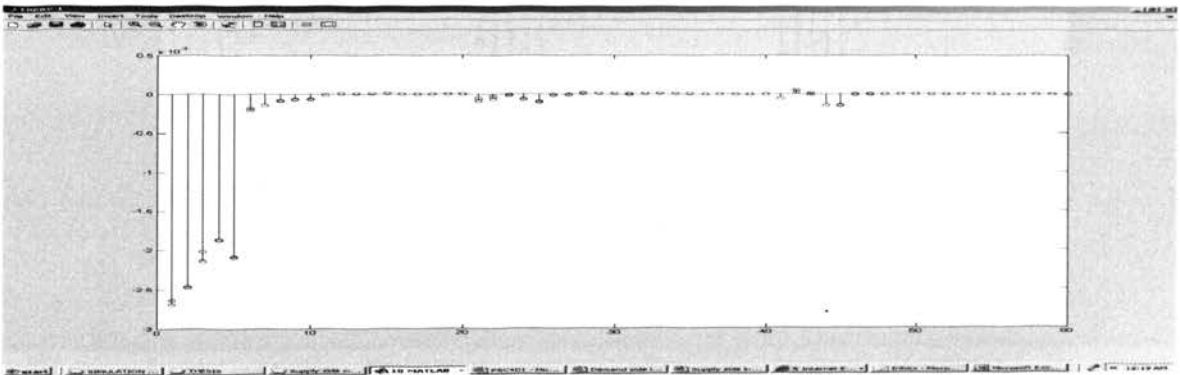


Figure22 Confidence intervals for the difference between flexibility index of order point and MRP (5 products)

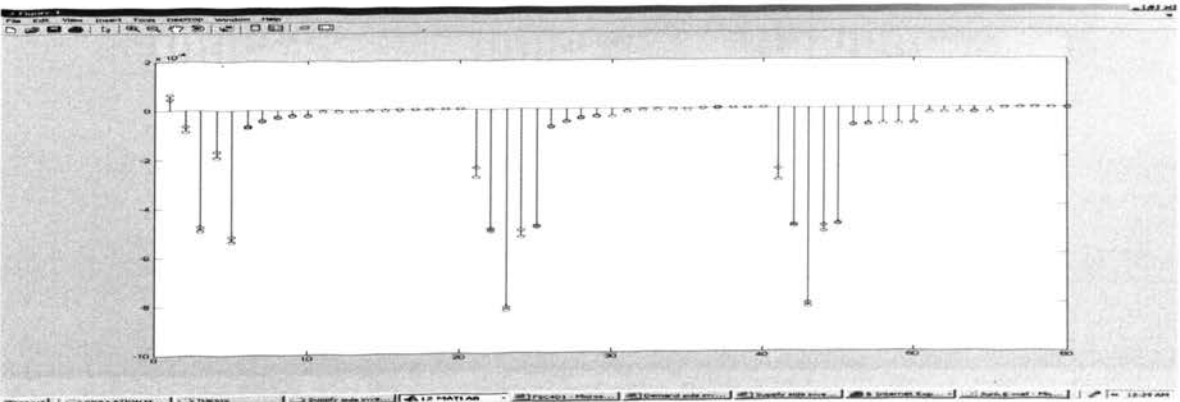


Figure23 Confidence intervals for the difference between flexibility index of order point and kanban (5 products)

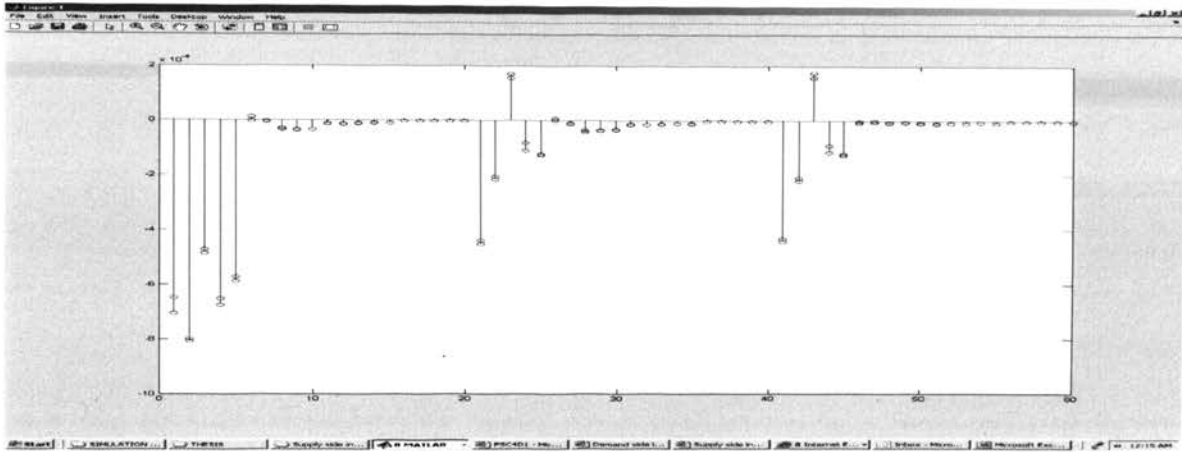


Figure24 Confidence intervals for the difference between flexibility index of kanban and MRP (10 products)

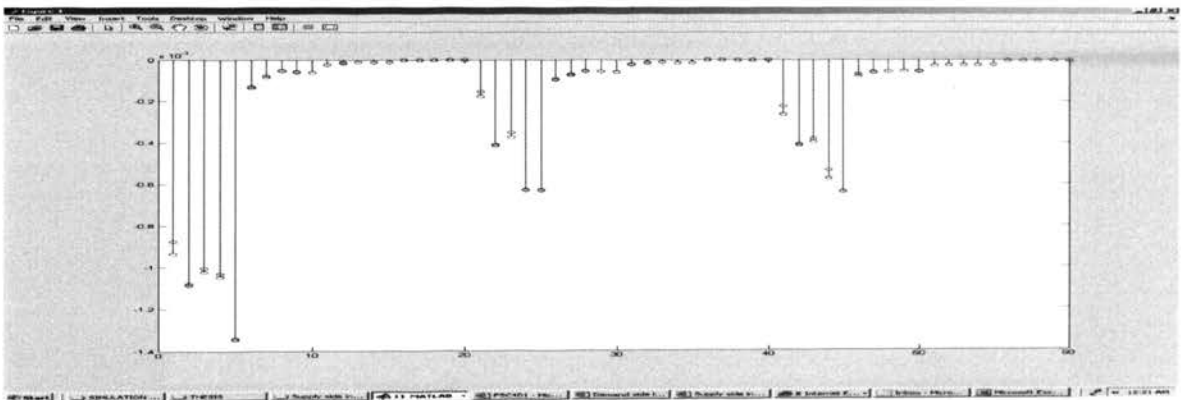


Figure25 Confidence intervals for the difference between flexibility index of order point and MRP (10 products)

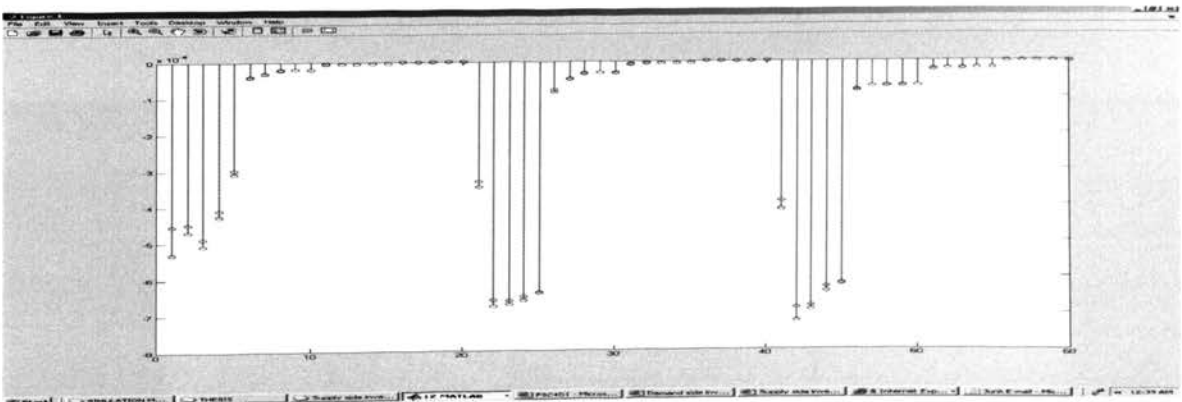


Figure26 Confidence intervals for the difference between flexibility index of order point and kanban (5 products)

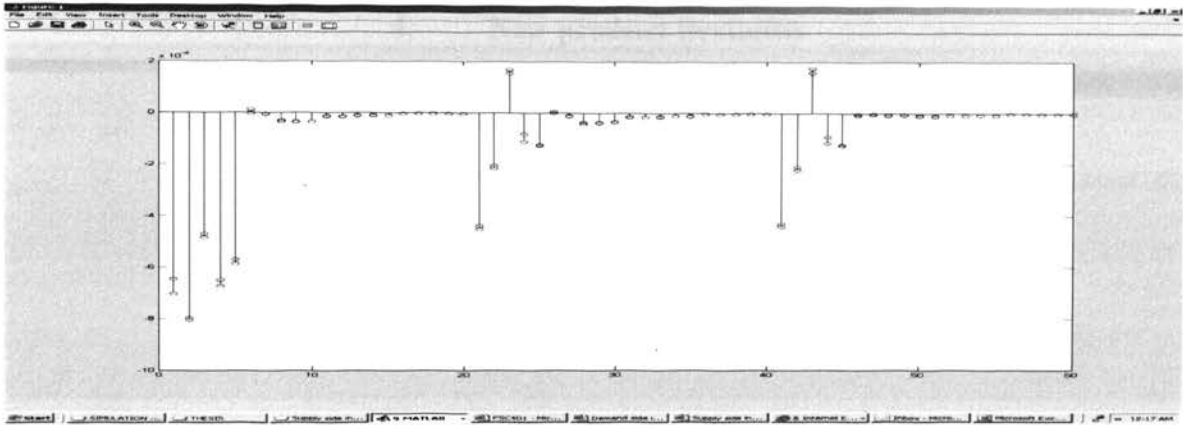


Figure27 Confidence intervals for the difference between flexibility index of kanban and MRP (15 products)

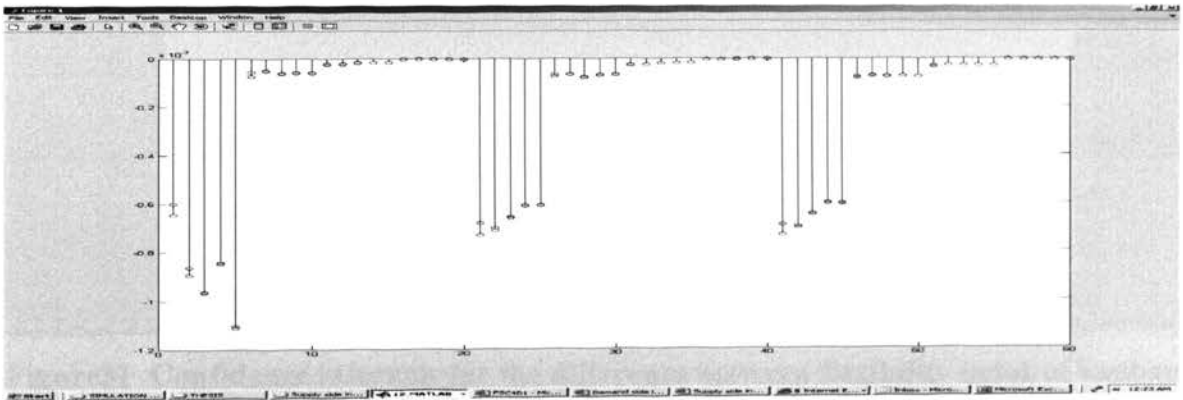


Figure28 Confidence intervals for the difference between flexibility index of order point and MRP (10 products)

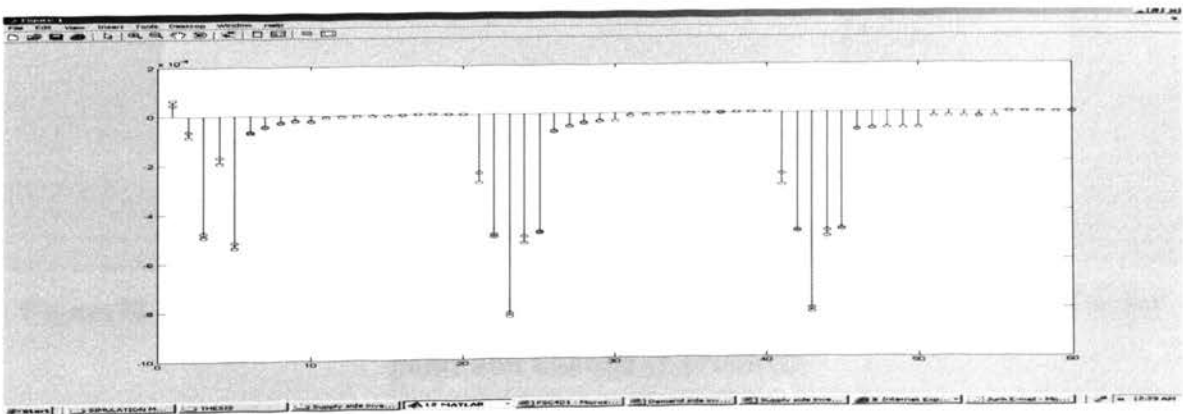


Figure29 Confidence intervals for the difference between flexibility index of order point and kanban (5 products)

4. New product flexibility

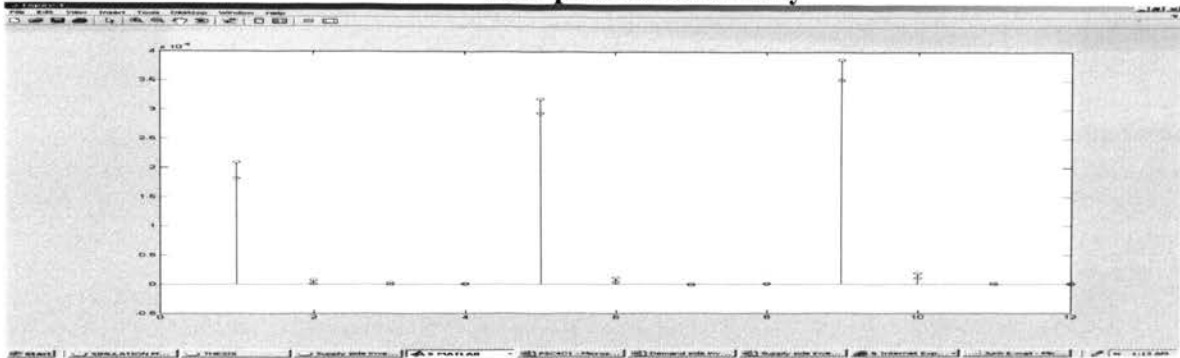


Figure30 Confidence intervals for the difference between flexibility index of order point and MRP (1 year)

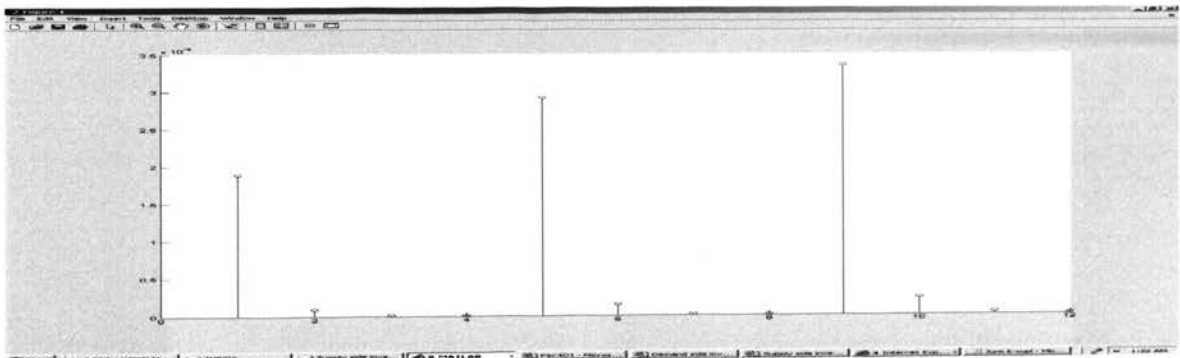


Figure31 Confidence intervals for the difference between flexibility index of kanban and MRP (1 year)

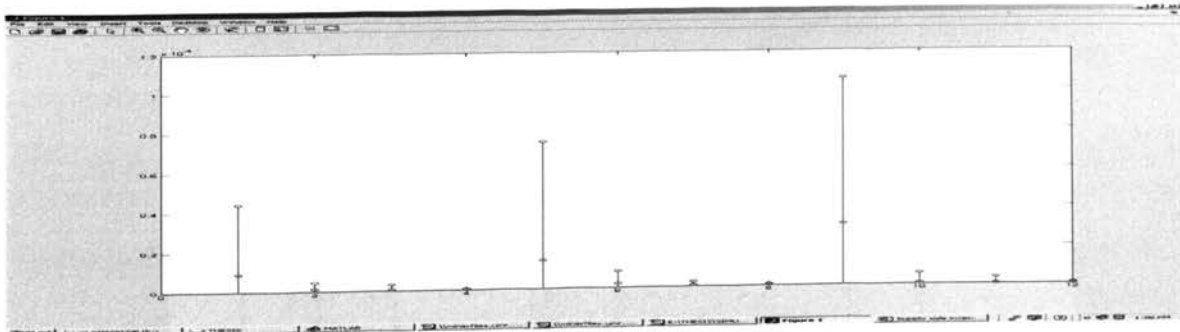


Figure32 Confidence intervals for the difference between flexibility index of order point and kanban (1 product)

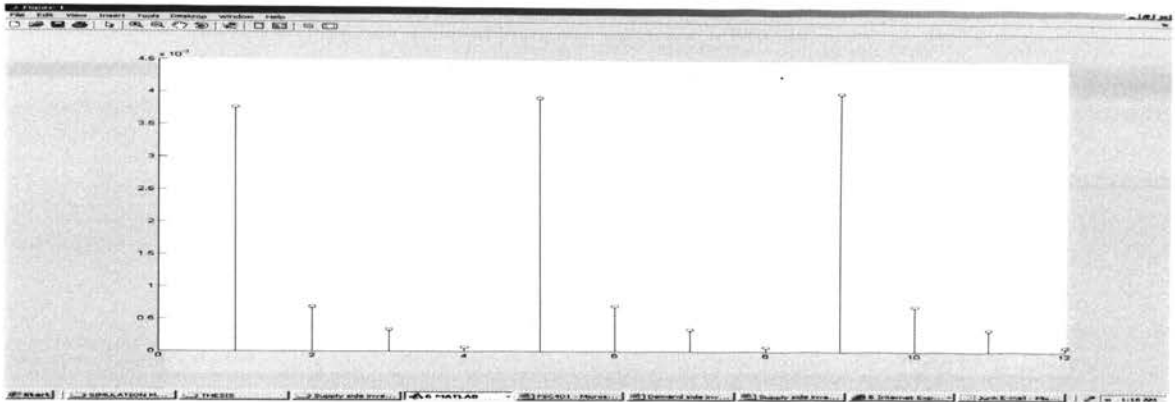


Figure33 Confidence intervals for the difference between flexibility index of order point and MRP (2 year)

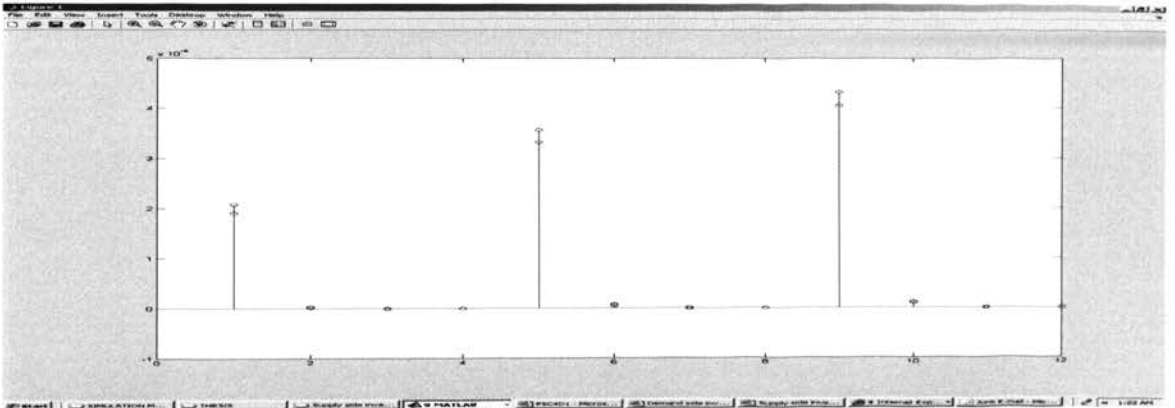


Figure34 Confidence intervals for the difference between flexibility index of kanban point and MRP (2 year)

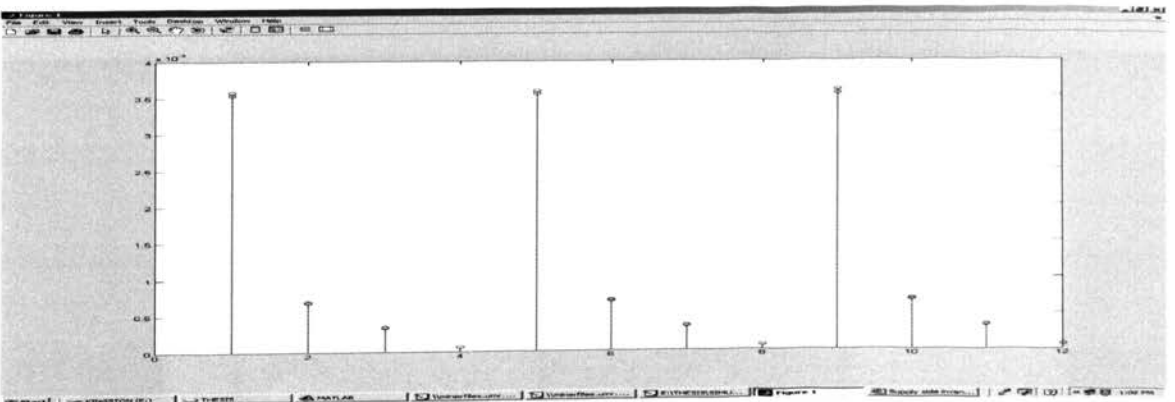


Figure35 Confidence intervals for the difference between flexibility index of order point and kanban (2 year)

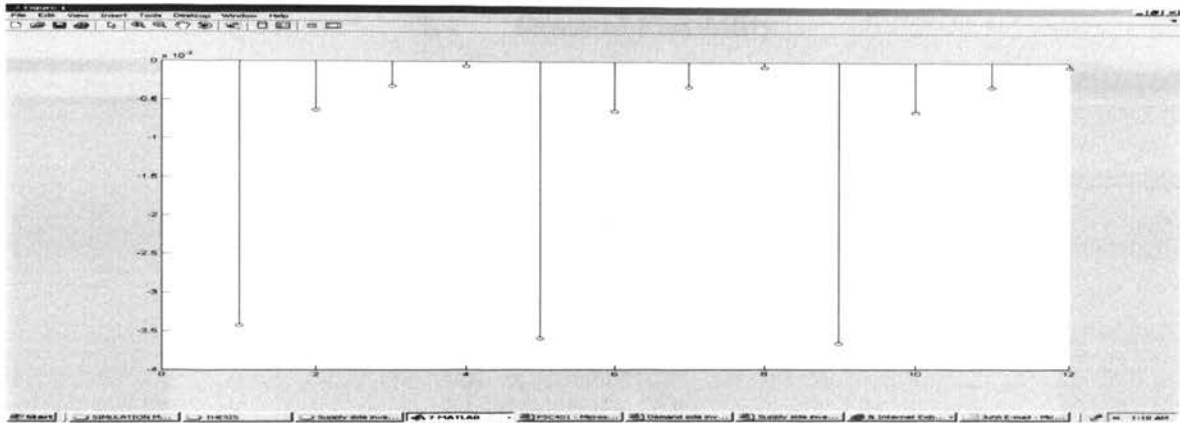


Figure36 Confidence intervals for the difference between flexibility index of order point and MRP (3 year)

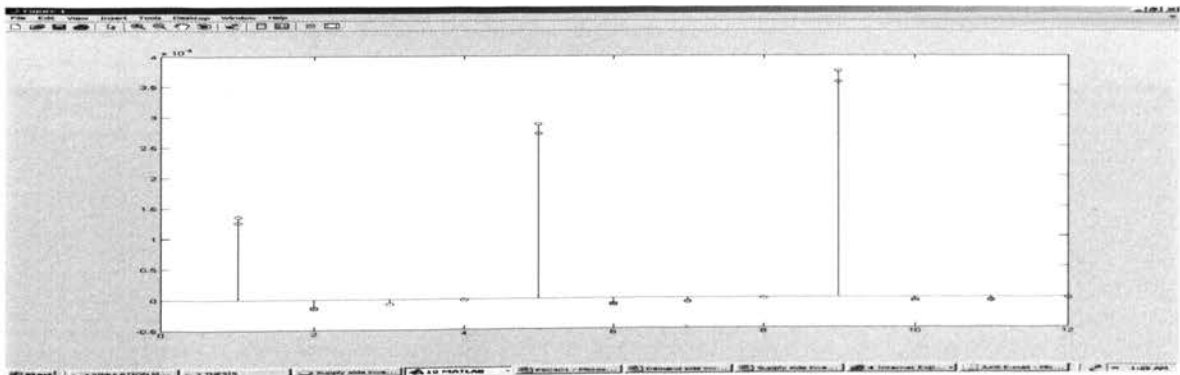


Figure37 Confidence intervals for the difference between flexibility index of kanban point and MRP (3 year)

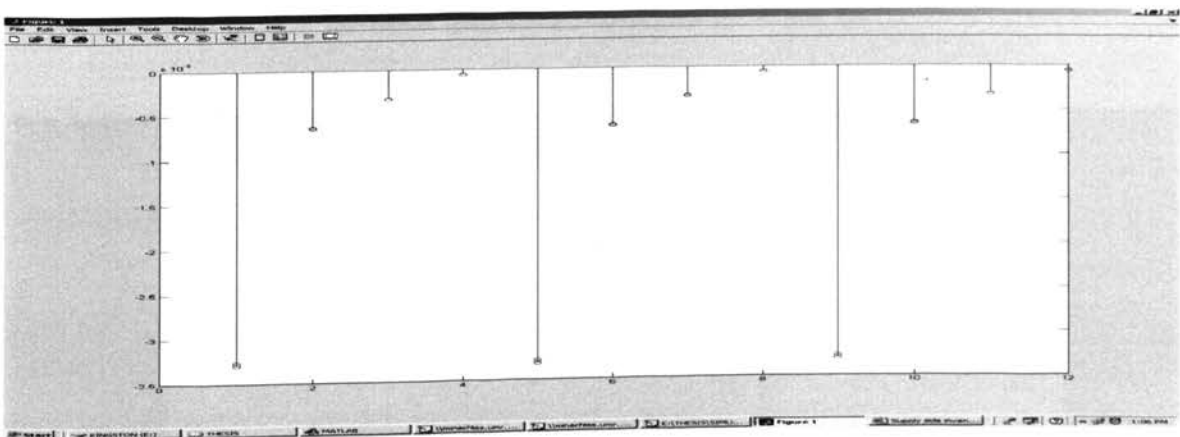


Figure38 Confidence intervals for the difference between flexibility index of order point and kanban (3 year)

1. Demand Flexibility

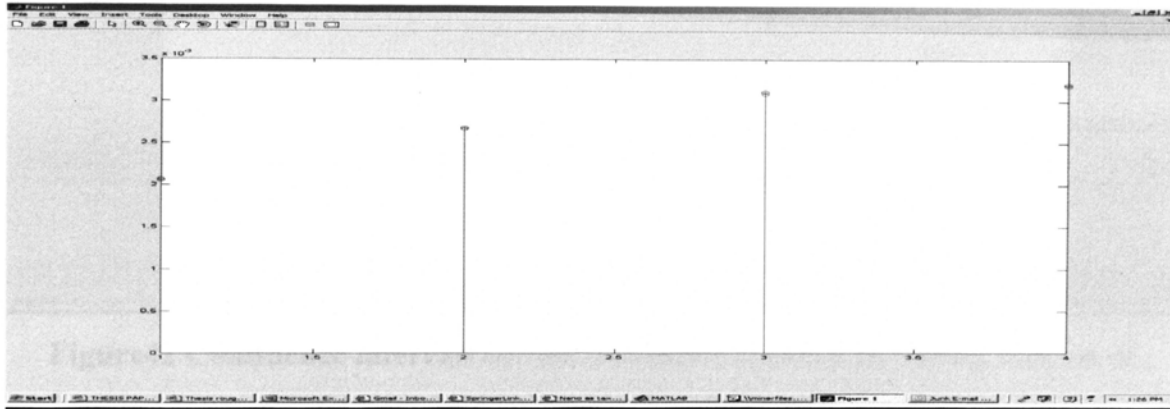


Figure39 Confidence intervals for the difference between flexibility indexes of assemble-to- order and make-to-stock (volume 1)

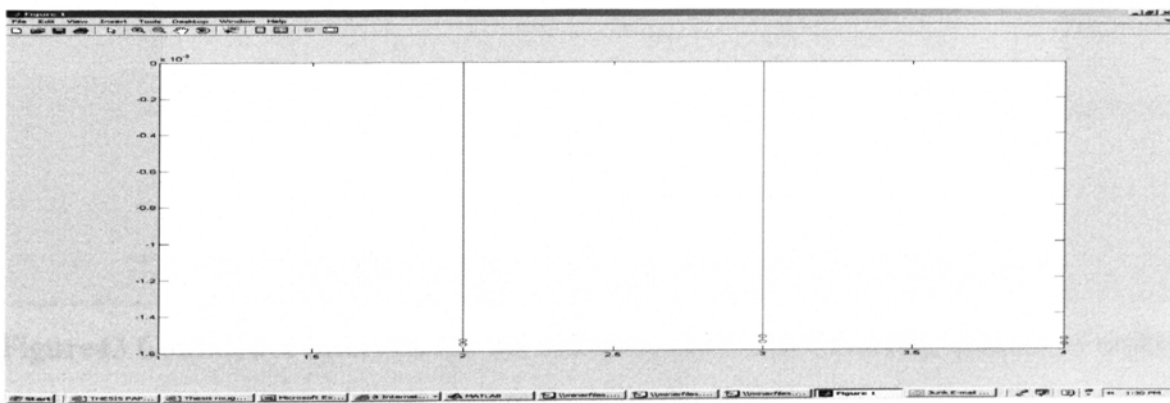


Figure40 Confidence intervals for the difference between flexibility indexes of make-to-stock and make-to-order (volume 1)

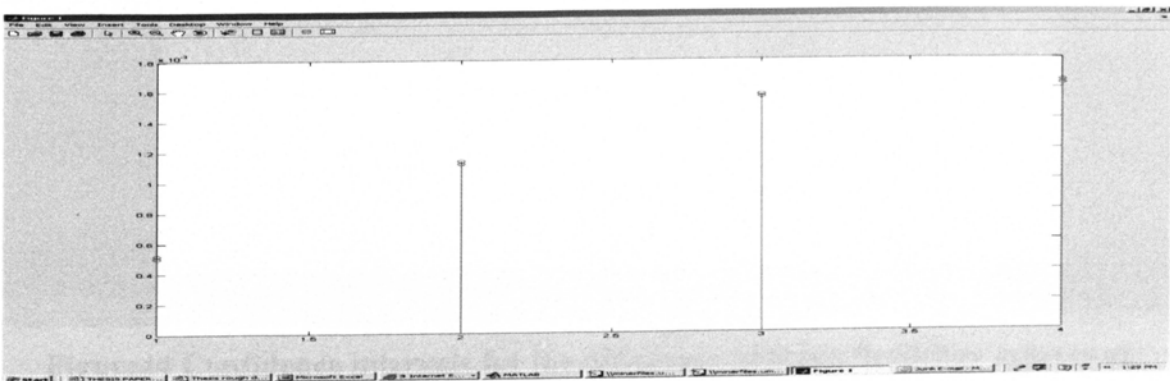


Figure41 Confidence intervals for the difference between flexibility indexes of assemble-to-order and make-to-order (volume 1)

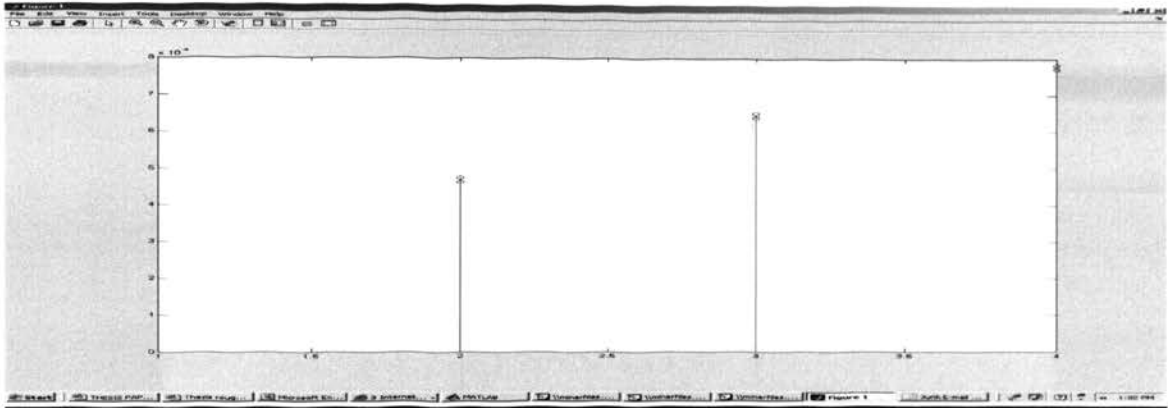


Figure42 Confidence intervals for the difference between flexibility indexes of assemble-to-order and make-to-stock (volume 2)

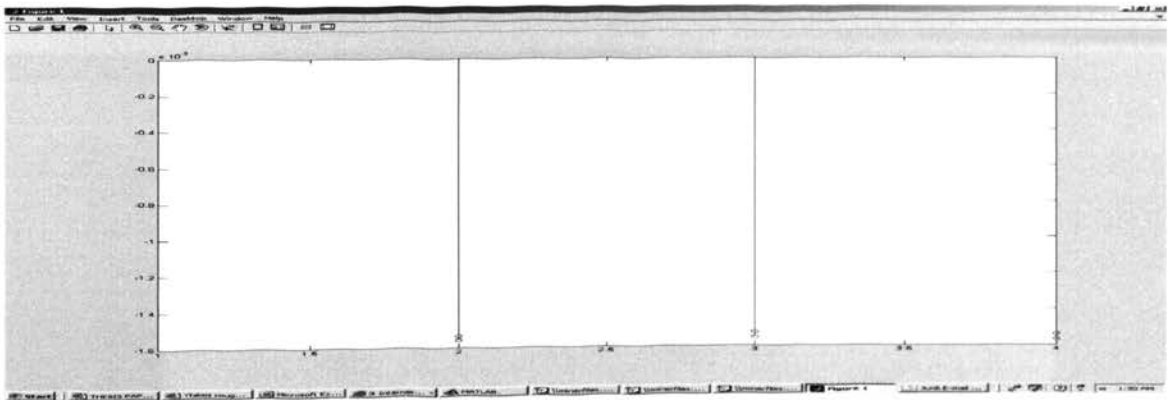


Figure43 Confidence intervals for the difference between flexibility indexes of make-to-stock and make-to-order (volume 2)

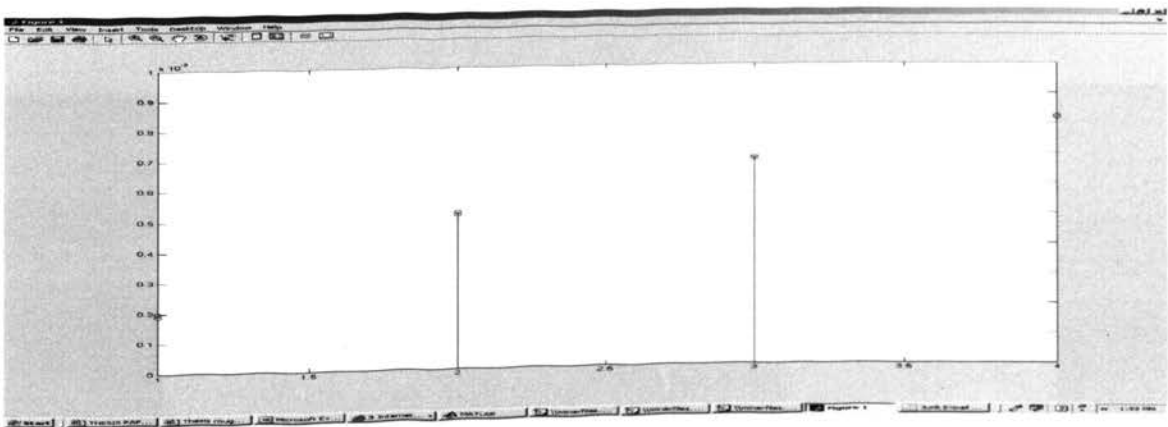


Figure44 Confidence intervals for the difference between flexibility indexes of assemble-to-order and make-to-order (volume 2)

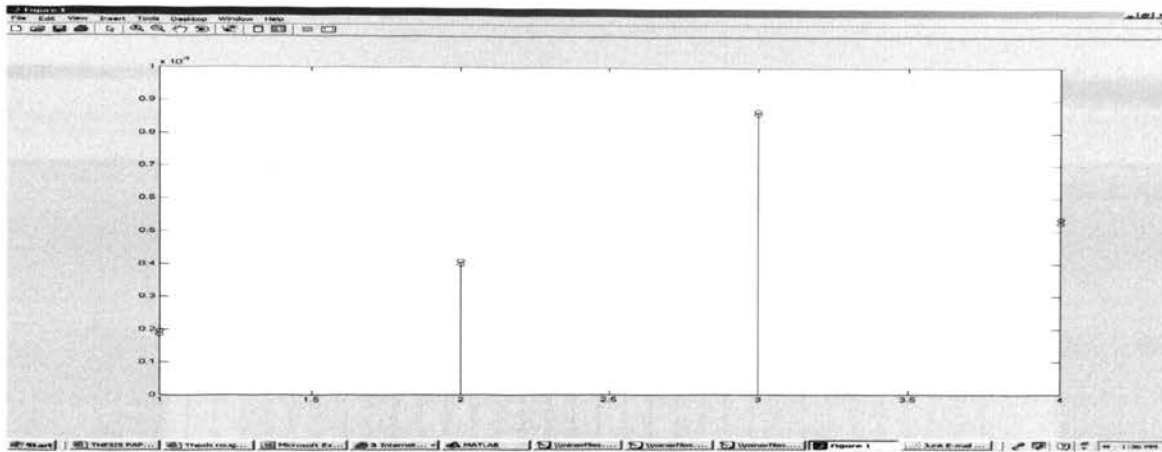


Figure45 Confidence intervals for the difference between flexibility indexes of assemble-to-order and make-to-stock (volume 3)

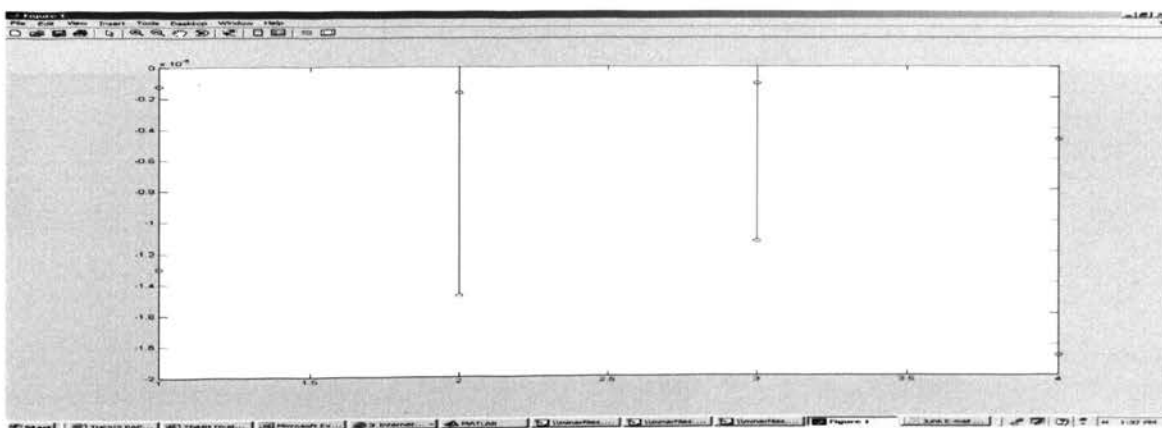


Figure46 Confidence intervals for the difference between flexibility indexes of make-to-stock and make-to-order (volume 3)

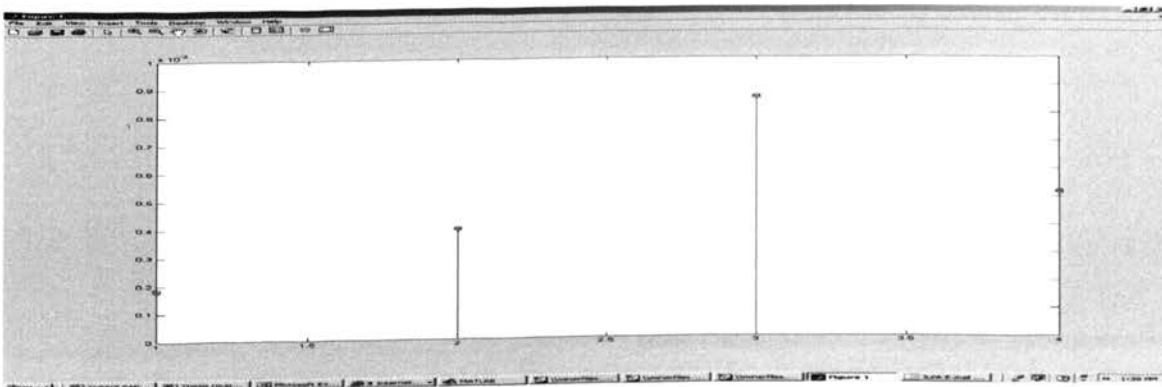


Figure47 Confidence intervals for the difference between flexibility indexes of assemble-to-order and make-to-order (volume 3)

2. Delivery flexibility

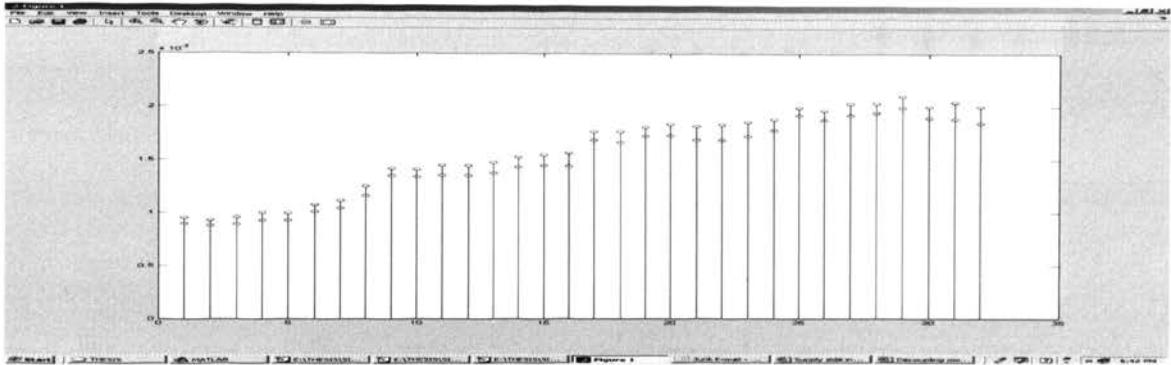


Figure48 Confidence intervals for the difference between flexibility indexes of assemble-to- order and make-to-stock

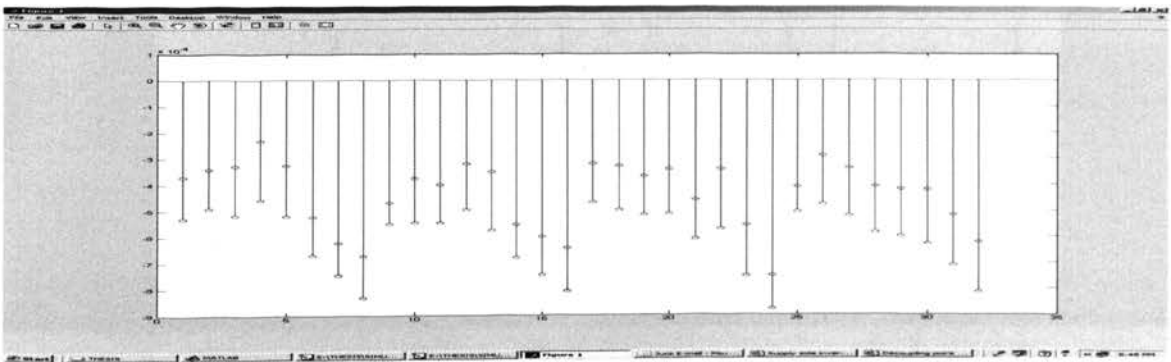


Figure49 Confidence intervals for the difference between flexibility indexes of make-to-stock and make-to-order

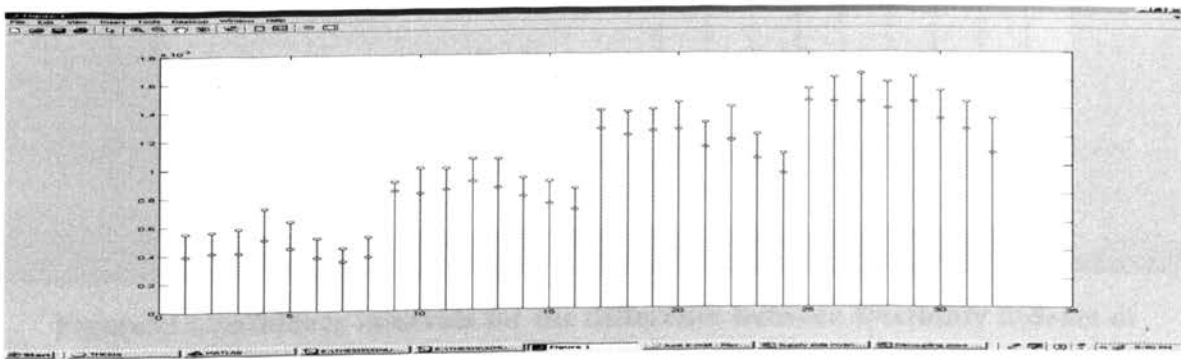


Figure50 Confidence intervals for the difference between flexibility indexes of assemble-to- order and make-to-order

3. Product mix flexibility

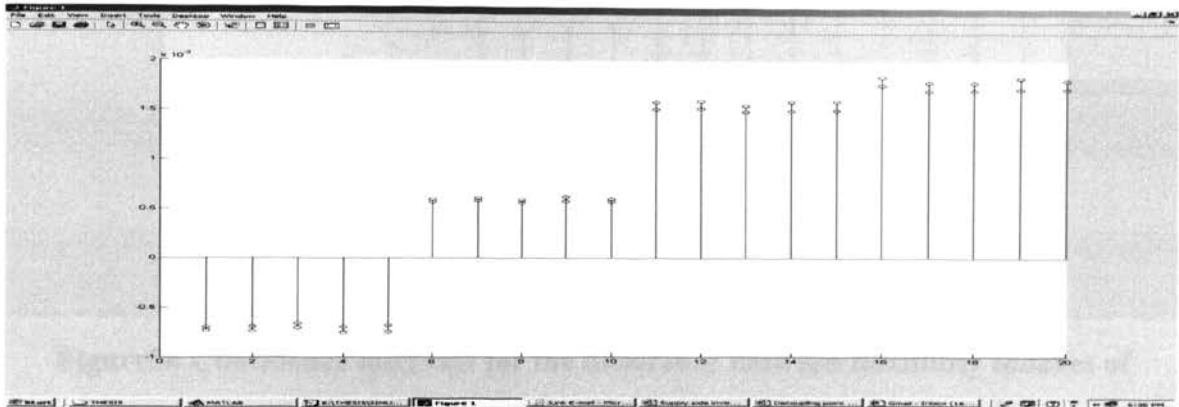


Figure51 Confidence intervals for the difference between flexibility indexes of assemble-to-order and make-to-stock (5 products)

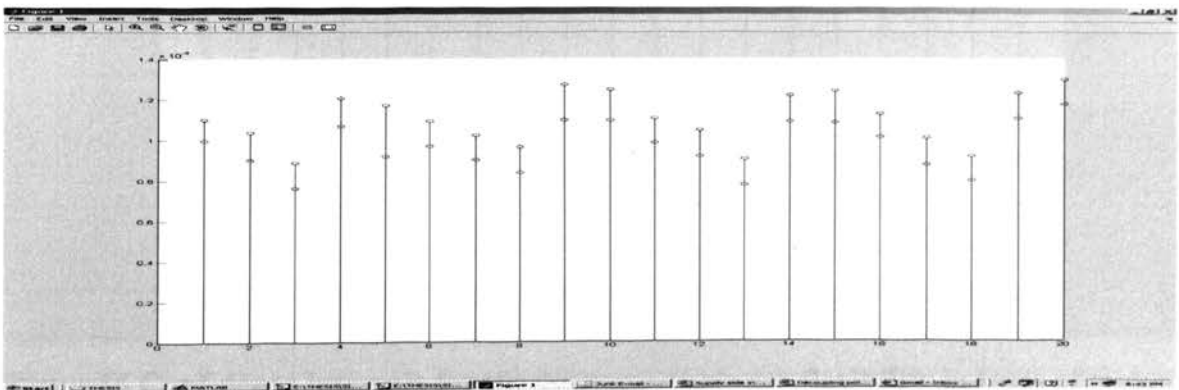


Figure52 Confidence intervals for the difference between flexibility indexes of make to stock and make to order (5 products)

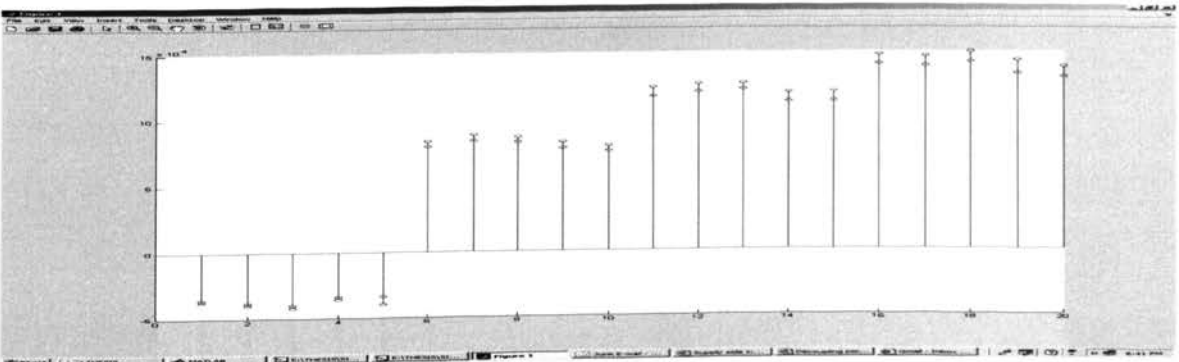


Figure53 Confidence intervals for the difference between flexibility indexes of assemble to order and make to order (5 products)

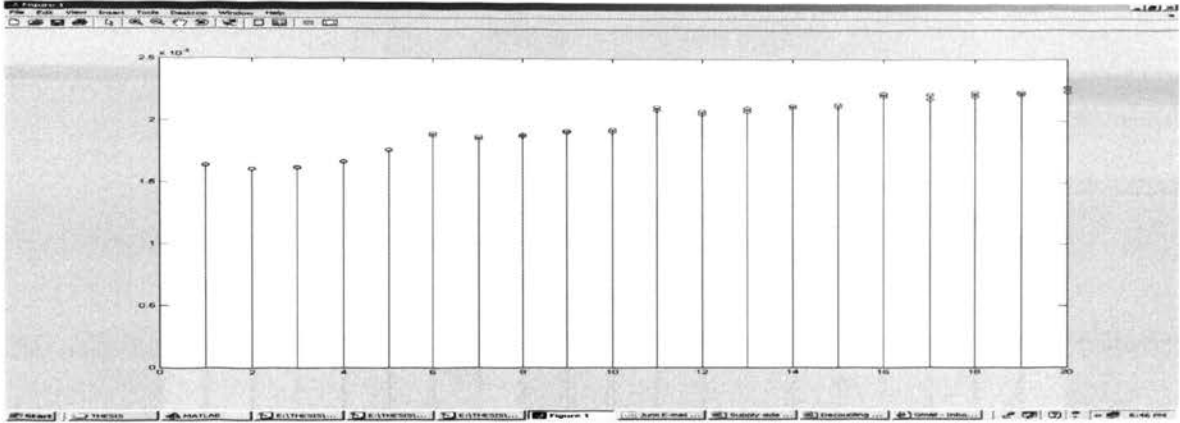


Figure54 Confidence intervals for the difference between flexibility indexes of assemble-to-order and make-to-stock (10 products)

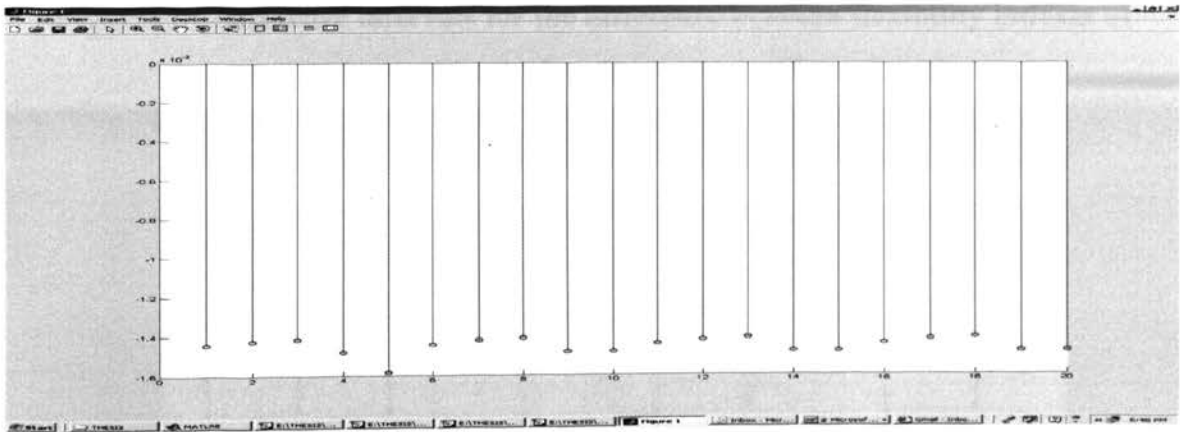


Figure55 Confidence intervals for the difference between flexibility indexes of make-to-stock and make-to-order (10 products)

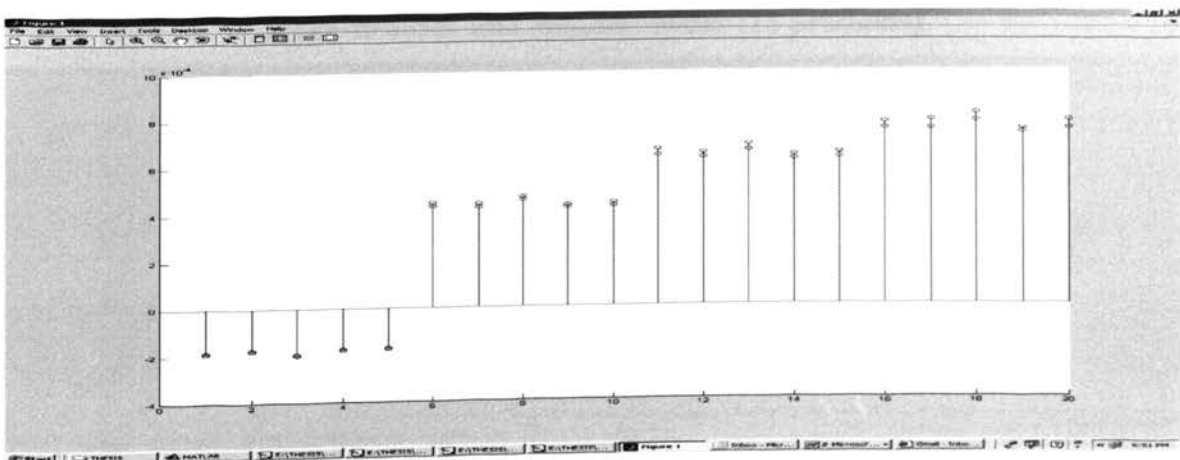


Figure56 Confidence intervals for the difference between flexibility indexes of assemble-to-order and make-to-order (10 products)

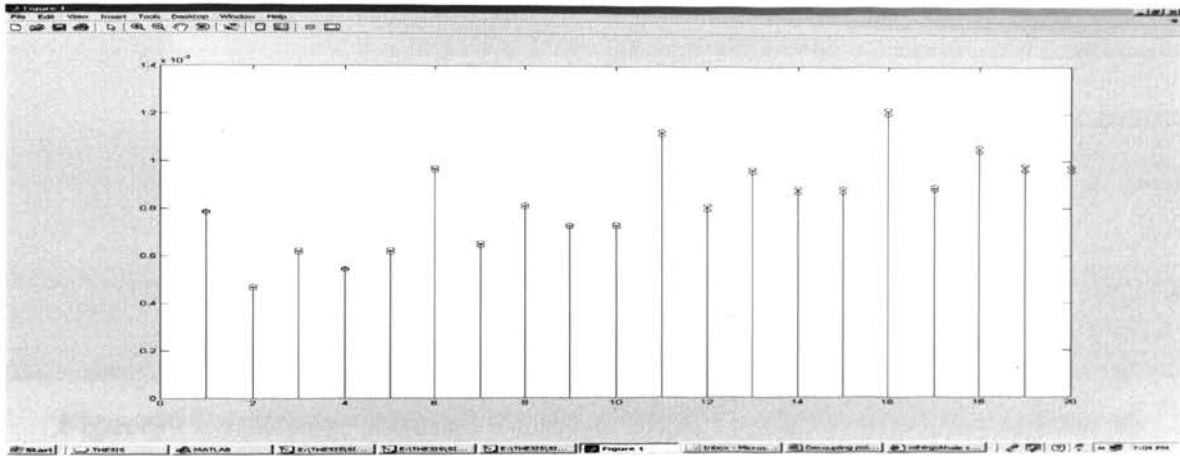


Figure 57 Confidence intervals for the difference between flexibility indexes of assemble-to-order and make-to-stock (15 products)

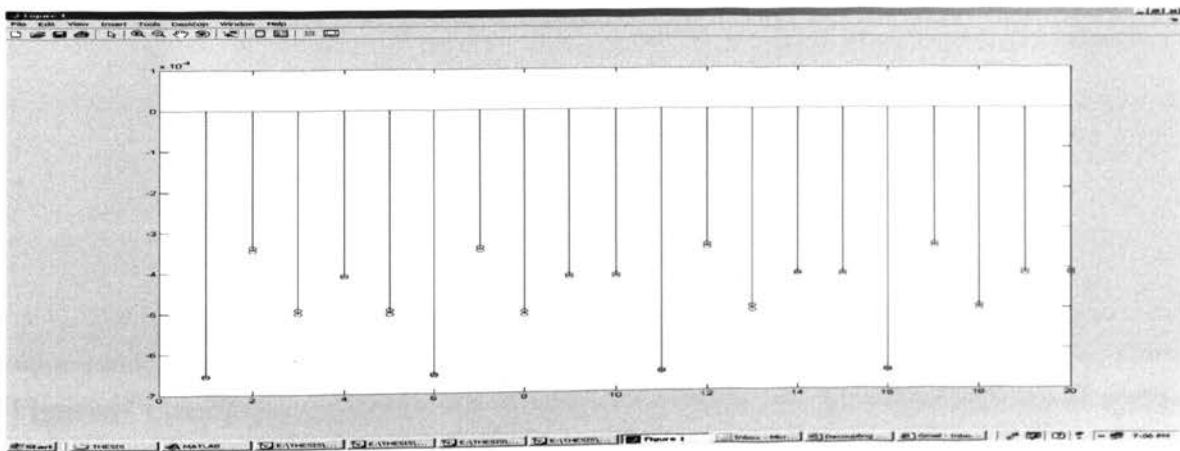


Figure 58 Confidence intervals for the difference between flexibility indexes of make-to-stock and make-to-order (15 products)

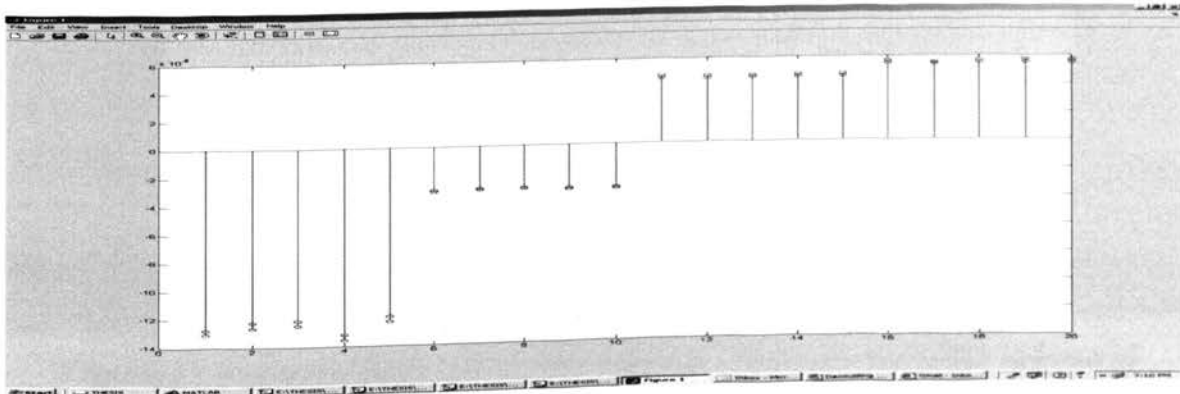


Figure 59 Confidence intervals for the difference between flexibility indexes of assemble-to-order and make-to-order (15 products)

4. New product flexibility

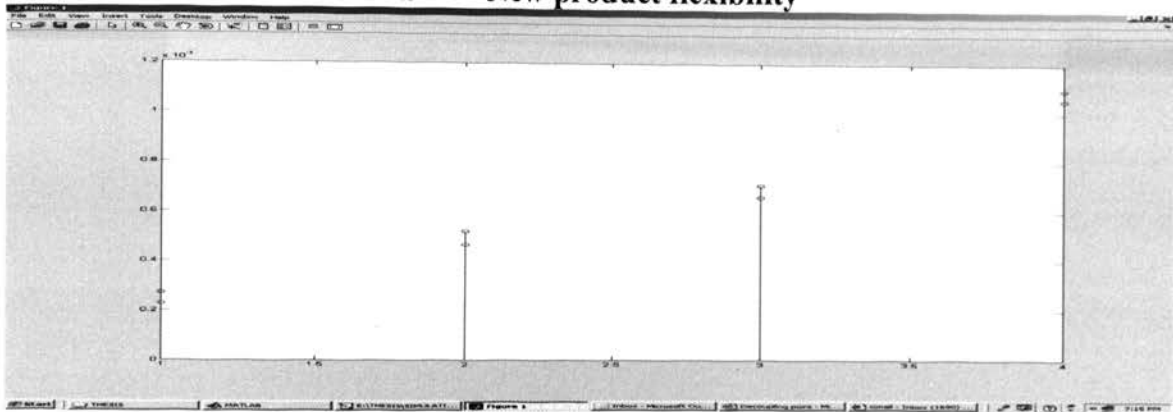


Figure60 Confidence intervals for the difference between flexibility indexes of assemble-to-order and make-to-stock (1 year)

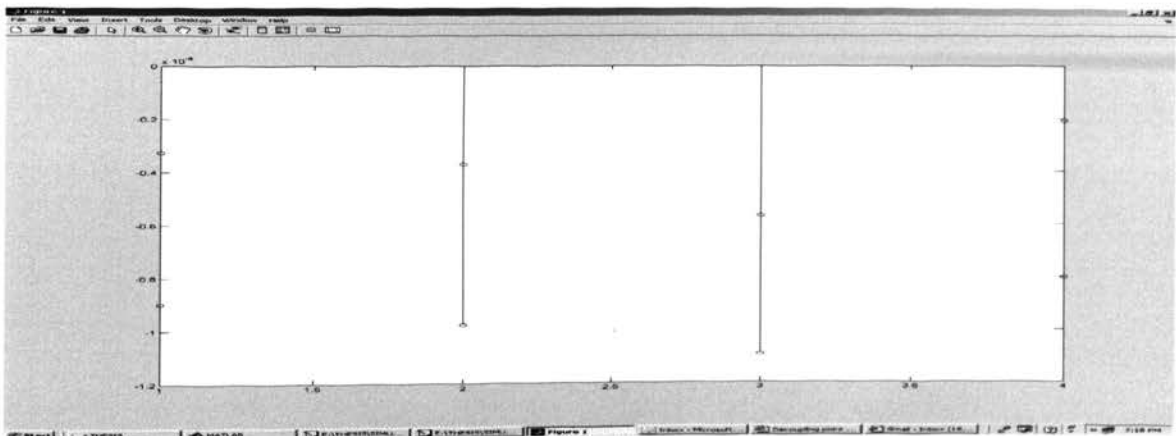


Figure61 Confidence intervals for the difference between flexibility indexes of make-to-stock and make-to-order (1 year)

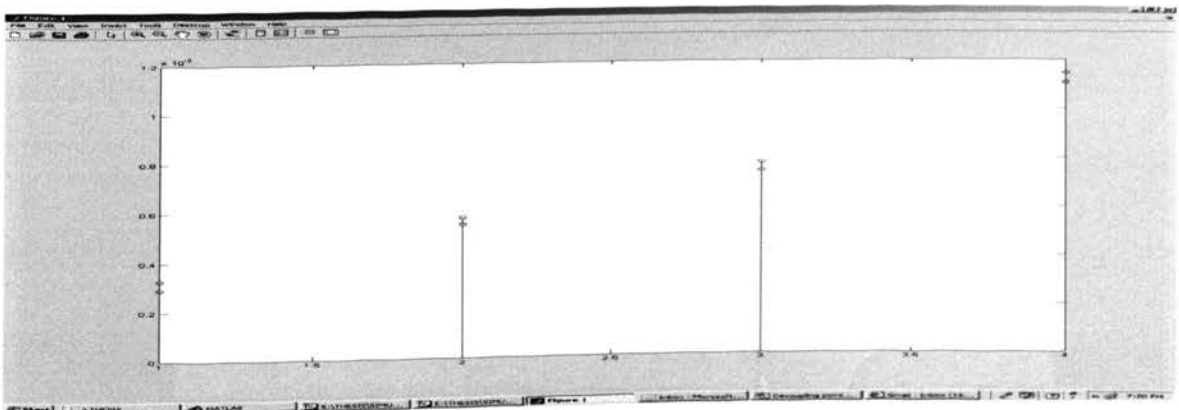


Figure62 Confidence intervals for the difference between flexibility indexes of assemble-to-order and make-to-order (1 year)

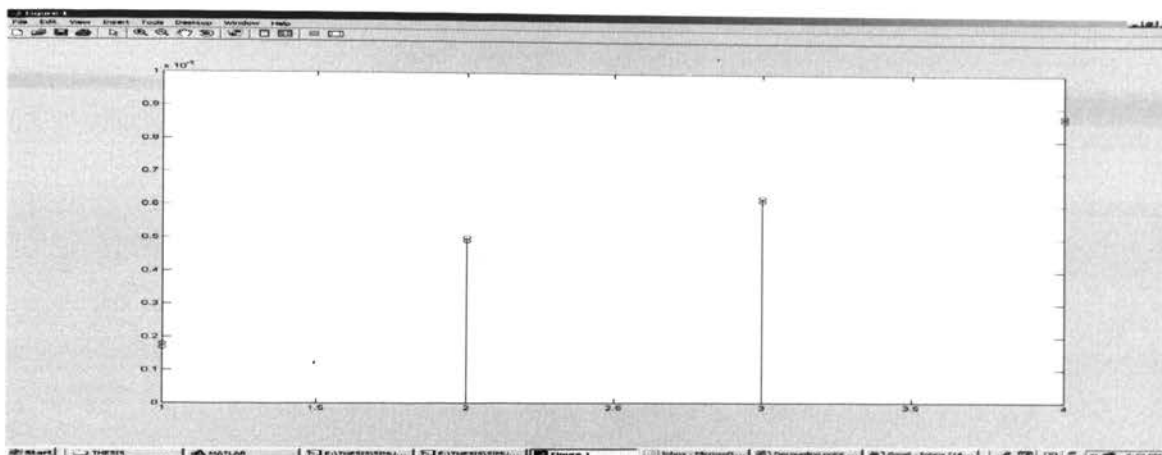


Figure63 Confidence intervals for the difference between flexibility indexes of assemble-to-order and make-to-stock (2 years)

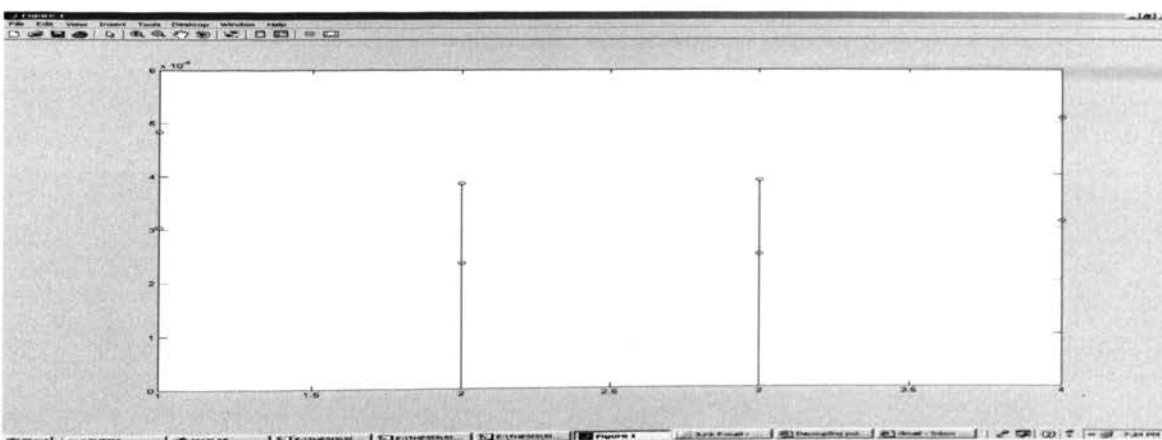


Figure64 Confidence intervals for the difference between flexibility indexes of make-to-stock and make-to-order (2 years)

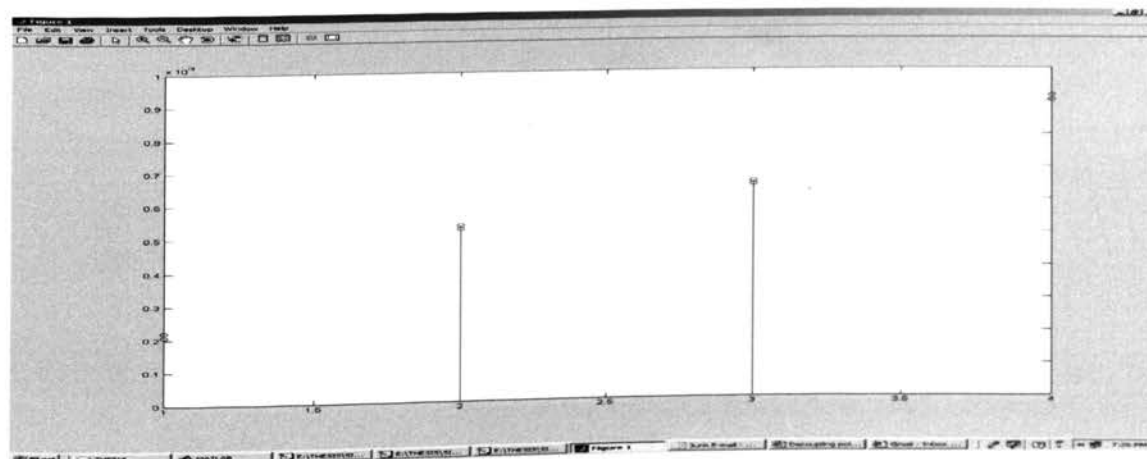


Figure64 Confidence intervals for the difference between flexibility indexes of assemble-to-order and make-to-order (2 years)

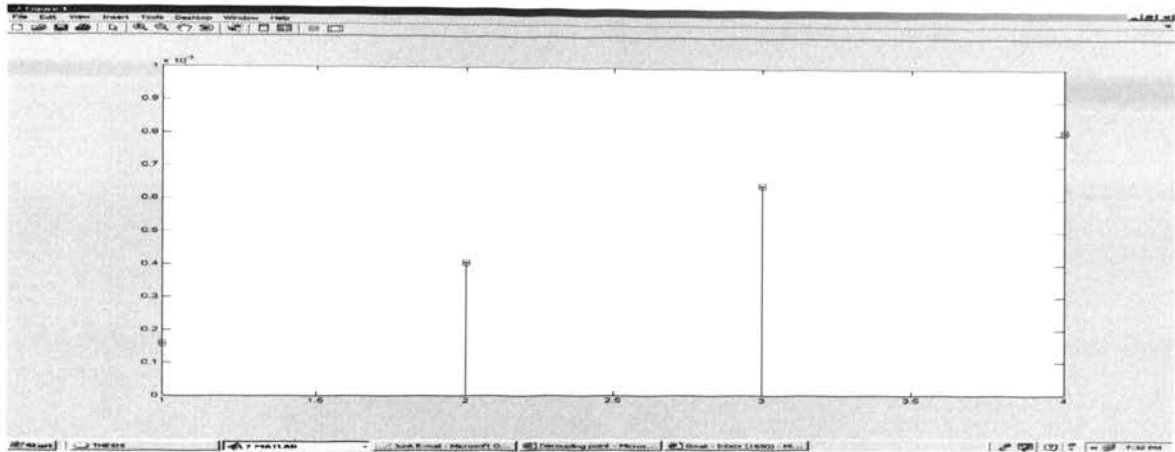


Figure65 Confidence intervals for the difference between flexibility indexes of assemble-to-order and make-to-stock (3 years)

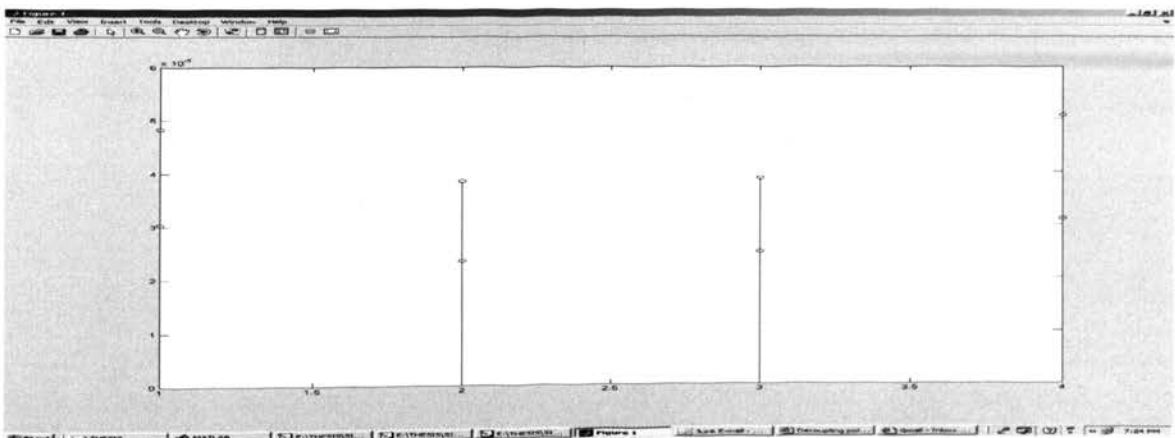


Figure66 Confidence intervals for the difference between flexibility indexes of make-to-stock and make-to-order (3 years)

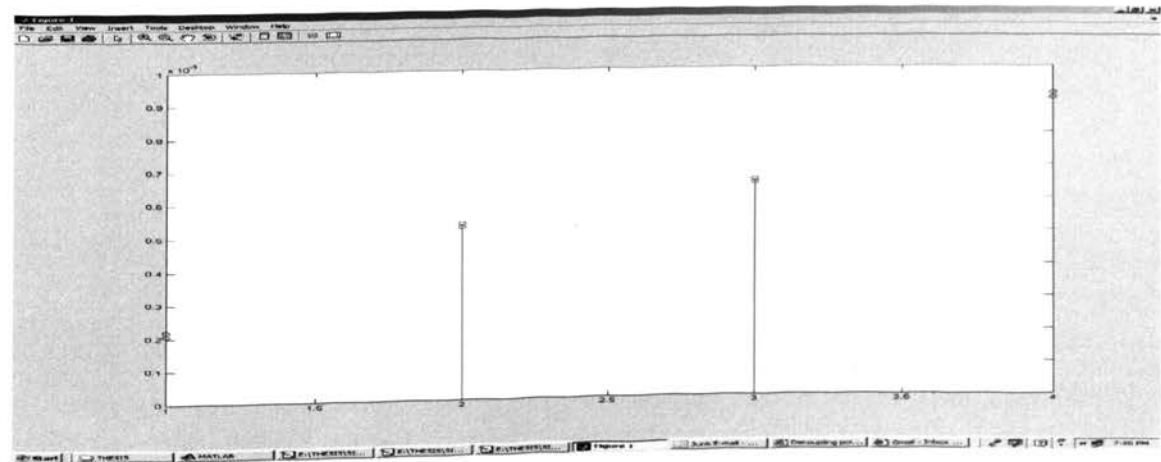


Figure67 Confidence intervals for the difference between flexibility indexes of assemble-to-order and make-to-order (3 year)

APPENDIX D
SIMULATION CODE

This appendix consists of the code that has been developed for simulation and statistical analysis in Mat lab 7.0. The simulation code is developed for all the alternatives of the following systems, 1) Demand side inventory control policy, 2) Supply side inventory control policy, and 3) Decoupling point.

Demand side inventory control policy

1. Distribution Requirement planning

```

    for i=1:n %no of products
    Q(i)=round( sqrt(2*D(i)*52*Kr(i)/hr(i)));%EOQ
    SSr(i)=round(SDr(i)*SLr); %safety stock
    RPr(i)=round(SSr(i)+Ltr*D(i)); %reorder point
    Mr(i)=round(Q(i)+RPr(i)); %maweek_inc lvl of inv
    Md(i)=Mr(i)*3;
    RPd(i)=RPr(i)*3;
end
%Orders from retailer for week 1
for i=1:n
    Sr(i,1)=Mr(i)-Fr(i,1);
    if Mr(i)-sum(Fr(i,1:1+Ltr))<0
        POr(i,1)=Mr(i)-(Mr(i)-sum(Fr(i,1:1+Ltr)));
        SRr(i,1+Ltr)=POr(i,1);
        Nr(i)=Nr(i)+1;
    end
end
%Orders from distributor for week1
for i=1:n
    Sd(i,1)=Md(i)-Fr(i,1);
    if Md(i)-sum(POR(i,1:1+Ltd))<0
        POd(i,1)=Md(i)-(Md(i)-sum(POR(i,1:1+Ltd)));
        SRm(i,1+Ltr)=POd(i,1);
        Nd(i)=Nd(i)+1;
    end
end
for t=start_week:end_week
    for i=1:n % Creating orders based on forecast(Retailer)
        Sr(i,t)= Sr(i,t-1)+SRr(i,t)-Fr(i,t);
        if (Sr(i,t-1)+sum(SRr(i,t:t+Ltr))-
sum(Fr(i,t:t+Ltr)))<0
            POr(i,t)=Mr(i)-(Sr(i,t-1)+sum(SRr(i,t:t+Ltr))-
sum(Fr(i,t:t+Ltr)));
            SRr(i,t+Ltr)=POr(i,t);
        end
    end
end
for t=start_week:end_week%Real scenario for frozen
interval(Retailer)
    for i=1:n
        if POr(i,1)>0% scheduled receipt from distributor
for 1st week
            SRd(i,1+Ltr)=POr(i,1);
        end
        Slr(i,1)=Mr(i)-Dr(i,1);
        Slr(i,t)=Slr(i,t-1)+SRd(i,t)+SB(i,t)-Dr(i,t);
        if Slr(i,t)<0 & Slr(i,t-1)>=0% Create back orders
            BOr(i,t)=abs(Slr(i,t));
        end
        if Slr(i,t)<0 & Slr(i,t-1)<0% Create back orders

```

```

        BOr(i,t)=abs(Slr(i,t-1)-Slr(i,t));
    end
end
%updating stock after frozen interval
%Real scenario for frozen interval(Distributor)
for i=1:n
    Sd(i,1)=Md(i)-POr(i,1);
    Sd(i,t)=Sd(i,t-1)+SRm(i,t)-POr(i,t);
    if POr(i,t)>0&Sd(i,t)>=0
        SRd(i,t+Ltr)=POr(i,t);
    end
    if POr(i,t)>0&Sd(i,t)<0&Sd(i,t-1)>0
        SRd(i,t+Ltr)=Sd(i,t-1);
        SB(i,t+Ltr+Ltd)=abs(Sd(i,t));
    end
    if (Sd(i,t-1)+sum(SRm(i,t:t+Ltd))-sum(POr(i,t:t+Ltd)))<0 & t<end_week
        POD(i,t)=Md(i)-(Sd(i,t-1)+sum(SRm(i,t:t+Ltd))-sum(POr(i,t:t+Ltd)));
        SRm(i,t+Ltd)=POD(i,t);
        Nd(i)=Nd(i)+1;
    end
    if t==end_week
        POD(i,end_week)=Md(i)-Sd(i,t);
        SRm(i,end_week+Ltd)=POD(i,end_week);
        Nd(i)=Nd(i)+1;
    end
    if POD(i,1)>0
        SRm(i,1+Ltd)=POD(i,1);
    end
end
end
start_week=end_week+1;
end_week=end_week+6;
end
%Computing performance measures
t=1;
for i=1:n
    for t=1:52
        if Slr(i,t)>0
            Ir(i)=Ir(i)+Slr(i,t);
            Id(i)=Id(i)+Sd(i,t);
        end
    end
    Iravg(i)=Ir(i)/52;
    Idavg(i)=Id(i)/52;
    DR(i)=sum(Dr(i,1:52));
    NBr(i)=ceil(sum(BOr(i,1:52))/52);
    Cr(i)=(Kr(i)/hr(i))*ceil(sum(POr(i,1:52))/52)+(NBr(i)*BH)
%+ Iravg(i)
    Cd(i)=(Kd(i)/hd(i))*ceil(sum(POD(i,1:52))/52)+Idavg(i);
    C(i)=Cr(i)+Cd(i);
end
CT=sum(C(1,1:n));
BO=sum(NBr(1,1:n));
DT=sum(DR(1,1:n));
SL=1-(BO/DT);
%Flexibility index
Alpha(c,x)=(SL/CT)*100;

```



```

end
Alpha1(c,1) =sum(Alpha(c,1:x))

```

2. Order Point

```

for i=1:n %no of products
    Q(i)=round( sqrt(2*D(i)*52*Kr(i)/hr(i))); %economic
order qty
    SSr(i)=round(SDr(i)*SLr); %safety stock
    RPr(i)=round(SSr(i)+Ltr*D(i)); %reorder point
    Mr(i)=round(Q(i)+RPr(i)); %maweek_inc lvl of inv
    Md(i)=Mr(i)*3;
    RPr(i)=RPr(i)*3;
end
for t=start_week:end_week
    for i=1:n%calcuating the stock for retailer and
creating purchase orders
        Sr(i,1)=Mr(i)-Dr(i,1);
        if Sr(i,1)<=RPr(i)
            POr(i,1)=Mr(i)-Sr(i,1);
            SRd(i,1+Ltr)=Mr(i)-Sr(i,1);
            SRr(i,1+Ltr)=Mr(i)-Sr(i,1);
        end
        Sr(i,t)= Sr(i,t-1) + SRd(i,t) + SB(i,t)-
Dr(i,t);
        if Sr(i,t-1) + sum(SRr(i,t:t+Ltr))-
Dr(i,t)<=RPr(i)
            POr(i,t)=Mr(i)-Sr(i,t);
            Nr(i)=Nr(i)+1;
            SRr(i,t+Ltr)=Mr(i)-Sr(i,t);
        end
        if Sr(i,t)<0 & Sr(i,t-1)<0% Create back orders
            BOr(i,t)=abs(Sr(i,t));
        end
        if Sr(i,t)<0 &Sr(i,t-1)<0% Create back orders
            BOr(i,t)=abs(Sr(i,t-1)-Sr(i,t));
        end
    end
    for i=1:n%calcuating the stock for distributor and
creating purchase orders
        Sd(i,1)=Md(i)-POr(i,1);
        if Sd(i,1)<=RPd(i)
            POd(i,1)=Md(i)-Sd(i,1);
            SRm(i,1+Ltd)=Md(i);
        end
        Sd(i,t)= Sd(i,t-1)+ SRm(i,t)-POr(i,t);
        if Sd(i,t)>=0&POr(i,t)>0
            SRd(i,t+Ltr)=POr(i,t);
        end
        if Sd(i,t)<0&POr(i,t)>0&Sd(i,t-1)>0
            SRd(i,t+Ltr)=Sd(i,t-1);
            SB(i,t+Ltr+Ltd)=abs(Sd(i,t));
        end
    end
end

```

```

                                if (Sd(i,t-1)+sum(SRm(i,t:t+Ltd))-
POr(i,t))<=RPd(i)
                                POd(i,t)=Md(i)-Sd(i,t);
                                Nd(i)=Nd(i)+1;
                                SRm(i,t+Ltd)=POd(i,t);
                                end
                                end
                                end
                                start_week=end_week+1;
                                end_week=end_week+6;
                                %put here new demand D (user input)
                                end
                                %Computing performance metrics
                                t=1;
                                for i=1:n
                                for t=1:52
                                if Sr(i,t)>0
                                Ir(i)=Ir(i)+Sr(i,t);
                                Id(i)=Id(i)+Sd(i,t);
                                end
                                end
                                Iravg(i)=Ir(i)/52;
                                Idavg(i)=Id(i)/52;
                                DR(i)=sum(Dr(i,1:52));
                                NBr(i)=ceil(sum(BOr(i,1:52))/52);

Cr(i)=(Kr(i)/hr(i))*ceil(sum(POr(i,1:52))/52)+(NBr(i)*BH) %+ Iravg(i)

Cd(i)=(Kd(i)/hd(i))*ceil(sum(POd(i,1:52))/52)%+Idavg(i);
C(i)=Cr(i)+Cd(i);
                                end
                                CT=sum(C(1,1:n));
                                BO=sum(NBr(1,1:n));
                                DT=sum(DR(1,1:n));
                                SL=1-(BO/DT);
                                %Flexibility index
                                Alpha(c,x)=(SL/CT)*100;
                                End

```

Supply side inventory control policy

1. Material Requirement Planning (MRP)

```

for x=1:30
    BOM=2
    n=5; %Number of products
    HM=1;
    for i=1:n
        var(1,i)=D(1,i)^2*.1*.1;
    end
    Vm=var;%variation in demand
    for j=1:3
        Km(j)=KM;
        hm(j)=HM;
        Ks(j)=KM;
        hs(j)=HM;
    end
    dmj=2*[(sum(D(1,1:2))) (sum(D(1,3:4))) D(1,5) ]%BOM explosion
    Vmj=2*[(sum(Vm(1,1:2))) (sum(Vm(1,3:4))) Vm(1,5) ]
    SDmj= round(sqrt(Vmj));
    start_week=2;
    end_week=6;
    total_weeks=54;
    Ltm=1; % lead time for transportation of components from supplier to
    manufacturer
    Lts=1; % lead time for production of components at supplier
    SLM=.99 %service level for manufacturer
    SLs=.99 %service level for supplier
    for j=1:3 %no of components
        Qm(j)=round( sqrt(2*dmj(j)*52*Km(j)/hm(j))); %economic order qty
    for manufacturer
        SSm(j)=round(SDmj(j)*SLm); %safety stock for manufacturer
        Mm(j)=round(Qm(j)+SSm(j)); %maweeek_inc level of inv
        RPm(j)= SSm(j)+(dmj(j)*Ltm);
        Ms(j)=3*Mm(j);
        RPs(j)=RPm(j)*3;
    end
    Sm=zeros(3,total_weeks+Ltm+5);
    SIm=zeros(3,total_weeks+Ltm+5);
    SRm=zeros(3,total_weeks+Ltm+5);
    SRs=zeros(3,total_weeks+Ltm+5);
    PRs=zeros(3,total_weeks+Lts+5);
    SB=zeros(3,total_weeks+Ltm+5);
    BOM=zeros(3,total_weeks+5);
    Ss=zeros(3,total_weeks+Lts+5);
    Fm=zeros(3,total_weeks+Ltm+5);
    Dm=zeros(3,total_weeks+Ltm+5);
    Om=zeros(3,total_weeks+Ltm+5);
    POM=zeros(3,total_weeks+Ltm+5);
    POS=zeros(3,total_weeks+Ltm+5);
    PRs=zeros(3,total_weeks+Lts+5);
    Nm=zeros(1,3);
    Ns=zeros(1,3);
    Im=zeros(3,1);

```

```

Is=zeros(3,1);
for j=1:3 % Forecasted and real demand for manufacturer
    Fm(j,:)=round(dmj(j)+ SDmj(j)*randn(total_weeks+Ltm+5,1));
    Dm(j,:)=round(dmj(j)+ SDmj(j)*randn(total_weeks+Ltm+5,1));
end
for j=1:3%creating orders for first week by manufacturer
    Sm(j,1)=Mm(j)-Fm(j,1);
    if Mm(j)-sum(Fm(j,1:1+Ltm))<0
        POm(j,1)=Mm(j)-(Mm(j)-sum(Fm(j,1:1+Ltm)));
        SRm(j,1+Ltm)=POm(j,1);
        Nm(j)=Nm(j)+1;
    end
end
for week=1:18
    for t=start_week:end_week
        for j=1:3 % Creating orders based on forecast for manufacturer
            Sm(j,t)= Sm(j,t-1)-Fm(j,t)+SRm(j,t);
            if (Sm(j,t-1)+sum(SRm(j,t:t+Ltm))-sum(Fm(j,t:t+Ltm)))<0
                POm(j,t)=Mm(j)-(Sm(j,t-1)+sum(SRm(j,t:t+Ltm))-
sum(Fm(j,t:t+Ltm)));
                SRm(j,t+Ltm)=POm(j,t);
            end
        end
    end
    for t=start_week:end_week
        for j=1:3
            Ss(j,1)=Ms(j)-POm(j,1);
            if POm(j,1)>0
                SRs(j,1+Lts)=POm(j,1);
            end
            Ss(j,t)=Ss(j,t-1)+PRs(j,t)-POm(j,t);
            if POm(j,t)>0& Ss(j,t)>=0% creating scheduled receipts for
manufacturer
                SRs(j,t+Ltm)=POm(j,t);
            end
            if POm(j,t)>0& Ss(j,t)<0& Ss(j,t-1)>0% creating scheduled
receipts for manufacturer
                SRs(j,t+Ltm)=Ss(j,t-1);
                SB(j,t+Ltm+Lts)=abs(Ss(j,t));
            end
            if Ss(j,t-1)+sum(PRs(j,t:t+Lts))-POm(j,t)<=RPs(j)%creating
production orders for supplier
                POs(j,t)=Ms(j)-Ss(j,t);
                PRs(j,t+Lts)=Ms(j)-Ss(j,t);
                Ns(j)=Ns(j)+1;
            end
        end
    end
    for j=1:3%Real scenario for frozen interval for manufacturer
        Slm(j,1)=Mm(j)-Dm(j,1);
        Slm(j,t)=Slm(j,t-1)+SRs(j,t)+SB(j,t)-Fm(j,t);
        if Slm(j,t)<0&Slm(j,t-1)>=0
            BOm(j,t)=ceil(abs(Slm(j,t)));%create back orders
        end
        if Slm(j,t)<0&Slm(j,t-1)<0
            BOm(j,t)=ceil(abs(Slm(j,t)-Slm(j,t-1)));%create back
orders
        end
    end
end

```

```

        end
    end
    for j=1:3
        Sm(j,end_week)=S1m(j,end_week);
    end
    start_week=end_week+1;
    end_week=end_week+3;
end
t=1;
    for j=1:3
        for t=1:52
            if S1m(j,t)>0
                Im(j)=Im(j)+S1m(j,t);
                Is(j)=Is(j)+Ss(j,t);
            end
        end
        Imavg(j)=Im(j)/52;
        Isavg(j)=Is(j)/52;
        POM(j)=ceil(sum(POm(j,1:52))/52)
        POS(j)=ceil(sum(POs(j,1:52))/52)
        DM(j)=sum(Dm(j,1:52));
        NBm(j)=ceil(sum(BOm(j,1:52))/52);
        Cm(j)=(Km(j)/hm(j))*POM(j)+(NBm(j)*BH) + Imavg(j)
        Cs(j)=(Ks(j)/hs(j))*POS(j)+Isavg(j);
        C(j)=Cm(j)+Cs(j);
    end
    CT=sum(C(1,1:3));
    BO=sum(NBm(1,1:3));
    DT=sum(dmj(1,1:3));
    SL=1-(BO/DT);
    %Flexibility index
    Alpha(c,x)=(SL/CT)*100;
end

```

2. Order point

```

for x=1:30
    n=5; %Number of products
    HM=1;
    for i=1:n
        var(1,i)=D(1,i)^2*.1*.1;
    end
    Vm=var;%variation in demand
    for j=1:3
        Km(j)=KM;
        hm(j)=HM;
        Ks(j)=KM;
        hs(j)=HM;
    end
    dmj=2*[(sum(D(1,1:2))) (sum(D(1,3:4))) D(1,5) ]%BOM explosion
    Vmj=2*[(sum(Vm(1,1:2))) (sum(Vm(1,3:4))) Vm(1,5) ]
    SDmj= round(sqrt(Vmj));
    start_week=2;
    end_week=6;

```

```

total_weeks=54;
Ltm=1; % lead time for transportation of components from
supplier to manufacturer
Lts=1; % lead time for production of components at supplier
SLm=.99 %service level for manufacturer
SLs=.99 %service level for supplier
for j=1:3 %no of components
    Qm(j)=round( sqrt(2*dmj(j)*52*Km(j)/hm(j))) %economic order
    qty for manufacturer
    SSm(j)=round(SDmj(j)*SLm) %safety stock for manufacturer
    RPm(j)=round(SSm(j)+dmj(j)*Lts);
    Mm(j)=round(Qm(j)+RPm(j)); %maweeek_inc level of inv
    Ms(j)=Mm(j)*3;
    RPs(j)=RPm(j)*3;
end
Sm=zeros(3,total_weeks+Ltm);
SRm=zeros(3,total_weeks+Ltm);
SRs=zeros(3,total_weeks+Ltm);
PRs=zeros(3,total_weeks+Lts);
SBs=zeros(3,total_weeks+Ltm);
Bom=zeros(3,total_weeks);
Ss=zeros(3,total_weeks+Lts);
Dm=zeros(3,total_weeks+Ltm);
Pom=zeros(3,total_weeks+Ltm);
PRs=zeros(3,total_weeks+Lts);
Nm=zeros(1,3);
Ns=zeros(1,3);
Im=zeros(3,1);
Is=zeros(3,1);
for j=1:3 % Forecasted and real demand for manufacturer
    Dm(j,:)=round(dmj(j)+ SDmj(j)*randn(total_weeks+Ltm,1));
end
for week=1:9
    for t=start_week:end_week%Real scenario for manufacturer
        for j=1:3
            Sm(j,1)=Mm(j)-Dm(j,1);
            Sm(j,t)=Sm(j,t-1)+SRs(j,t)+SBs(j,t)-Dm(j,t);
            if Sm(j,t-1)+sum(SRm(j,t:t+Ltm))-Dm(j,t)<=RPm(j)
                Pom(j,t)=Mm(j)-Sm(j,t);
                SRm(j,t+Ltm)=Mm(j)-Sm(j,t);
                Nm(j)=Nm(j)+1;
            end
            if Sm(j,t)<0 % Create back orders
                Bom(j,t)=abs(Sm(j,t));
            end
        end
        for j=1:3
            Ss(j,1)=Ms(j)-Pom(j,1);
            if Pom(j,1)>0
                SRs(j,1+Ltm)=Pom(j,1);
            end
            Ss(j,t)=Ss(j,t-1)+PRs(j,t)-Pom(j,t);
            if Pom(j,t)>0& Ss(j,t)>0||Ss(j,t)==0% creating
scheduled receipts for manufacturer
                SRs(j,t+Ltm)=Pom(j,t);
            end
        end
    end
end

```

```

        if POm(j,t)>0& Ss(j,t)<0& Ss(j,t-1)>0% creating
scheduled receipts for manufacturer
            SRs(j,t+Ltm)=Ss(j,t-1);
            SBs(j,t+Ltm+Lts)=POm(j,t)-Ss(j,t-1);
        End
if Ss(j,t-1)+sum(PRs(j,t:t+Lts))-POm(j,t)<=RPs(j)%creating production
orders for supplier
            POs(j,t)=Ms(j)-Ss(j,t);
            PRs(j,t+Lts)=Ms(j)-Ss(j,t);
            Ns(j)=Ns(j)+1;
        end
    end
end
start_week=end_week+1;
end_week=end_week+6;
end
t=1;
for j=1:3
    for t=1:52
        if Sm(j,t)>0
            Im(j)=Im(j)+Sm(j,t);
            Is(j)=Is(j)+Ss(j,t);
        end
    end
    Imavg(j)=Im(j)/2;
    Isavg(j)=Is(j)/2;
    POM(j)=ceil(sum(POm(j,1:52))/52)
    POS(j)=ceil(sum(POs(j,1:52))/52)
    DM(j)=sum(Dm(j,1:52));
    NBm(j)=ceil(sum(BOm(j,1:52))/52);
    Cm(j)=(Km(j)/hm(j))*POM(j)+(NBm(j)*BH) + Imavg(j)
    Cs(j)=(Ks(j)/hs(j))*POS(j)+Isavg(j);
    C(j)=Cm(j)+Cs(j);
end
CT=sum(C(1,1:3));
BO=sum(NBm(1,1:3));
DT=sum(dmj(1,1:3));
SL=1-(BO/DT);
%Flexibility index
Alpha(c,x)=(SL/CT)*100;
end

```

3. Kanban

```

for x=1:30
    n=5; %Number of products
    HM=1;
    for i=1:n
        var(1,i)=D(1,i)^2*.1*.1;
    end
    Vm=var;%variation in demand
    for j=1:3
        Km(j)=KM;
        hm(j)=HM;
    end
end

```

```

        Ks(j)=KM;
        hs(j)=HM;
    end
    dmj=2*[(sum(D(1,1:2))) (sum(D(1,3:4))) D(1,5) ]%BOM explosion
    Vmj=2*[(sum(Vm(1,1:2))) (sum(Vm(1,3:4))) Vm(1,5) ]
    SDmj= round(sqrt(Vmj));
    start_week=2;
    end_week=6;
    total_weeks=54;
    Ltm=1; % lead time for transportation of components from
supplier to manufacturer
    Lts=1; % lead time for production of components at supplier
    SLm=.99 %service level for manufacturer
    SLs=.99 %service level for supplier
    for j=1:3 %no of components
        Qm(j)=round( sqrt(2*dmj(j)*52*Km(j)/hm(j))) %economic order
qty for manufacturer
        SSm(j)=round(SDmj(j)*SLm) %safety stock for manufacturer
        RPm(j)=round(dmj(j)*(Ltm+round(SSm(j)/dmj(j)))));
        km(j)=ceil(RPm(j)/Qm(j));
        Ms(j)= km(j)*3*Qm(j);
        RPs(j)=RPm(j)*3;
    end
    Sm=zeros(4,total_weeks+Ltm);
    SRm=zeros(4,total_weeks+Ltm);
    SRs=zeros(4,total_weeks+Ltm);
    PRs=zeros(4,total_weeks+Lts);
    SB=zeros(4,total_weeks+Ltm);
    BOm=zeros(4,total_weeks);
    Ss=zeros(4,total_weeks+Lts);
    Dm=zeros(4,total_weeks+Ltm);
    POm=zeros(4,total_weeks+Ltm);
    POs=zeros(4,total_weeks+Ltm);
    PRs=zeros(4,total_weeks+Lts);
    k1m=zeros(4,total_weeks+Lts);
    KRm=zeros(4,total_weeks+Lts);
    KRs=zeros(4,total_weeks+Lts);
    mk=zeros(4,total_weeks+Lts);
    Nm=zeros(1,3);
    Ns=zeros(1,3);
    Im=zeros(3,1);
    Is=zeros(3,1);

    for j=1:3 % Forecasted and real demand for manufacturer
        Dmj(j,:)=round(dmj(j)+ SDmj(j)*randn(total_weeks+Ltm,1));
    end
    for j=1:3
        k1m(j,1)=km(j);
    end
    for j=1:3%kanban ordering for the first week
        if k1m(j,1)>0
            mk(j,1)=ceil(Dmj(j,1)/Qm(j));%move the first kanban to
production line
            k1m(j,1)=k1m(j,1)-mk(j,1);
            Sm(j,1)=(mk(j,1)*Qm(j))-Dmj(j,1);
        end
        if k1m(j,1)+sum(KRm(j,1:Ltm))<=km(j)

```



```

                                KOm(j,1)=km(j)-k1m(j,1);%ordering kanbans for the 1st
week
                                POm(j,1)=KOm(j,1);
                                KRm(j,1+Ltm)=KOm(j,1);
                                end
                                end
                                for week=1:9
                                    for t=start_week:end_week%Real scenario for manufacturer
                                        for j=1:3
                                            KRs(j,2)=KOm(j,1);
                                            k1m(j,t)=k1m(j,t-1)+KRs(j,t);
                                            Sm(j,t)=Sm(j,t-1)-Dmj(j,t);%inventory in production
line.
                                            if Sm(j,t)<=0 & k1m(j,t)>0%moving kanbans to the
production line
                                                mk(j,t)=ceil(abs(Sm(j,t))/Qm(j));
                                                k1m(j,t)=k1m(j,t)-mk(j,t);
                                                Sm(j,t)=Sm(j,t-1)+(mk(j,t)*Qm(j))-
Dmj(j,t)+SRs(j,t)
                                            end
                                            if Sm(j,t)<=0&k1m(j,t)<=0&Sm(j,t-1)>=0
                                                BOm(j,t)=abs(Sm(j,t));%create back orders
                                            end
                                            if Sm(j,t)<=0&k1m(j,t-1)<=0&Sm(j,t-1)<0
                                                BOm(j,t)=abs(Sm(j,t)-Sm(j,t-1));%create back
orders
                                            end
                                if k1m(j,t-1)+sum(KRm(j,t:t+Ltm))-mk(j,t)<km(j)%ordering kanban logic
                                    KOm(j,t)=km(j)-k1m(j,t);
                                    POm(j,t)=KOm(j,t)*Qm(j);
                                    KRm(j,t+Ltm)=KOm(j,t);
                                end
                                end
                                for j=1:3
                                    Ss(j,1)=Ms(j)-POm(j,1);
                                    Ss(j,t)=Ss(j,t-1)+PRs(j,t)-POm(j,t);
                                    if POm(j,t)>0& Ss(j,t)>=0% creating scheduled
reciepts for manufacturer
                                        KRs(j,t+Ltm)=KOm(j,t);
                                    end
                                    if POm(j,t)>0& Ss(j,t)<0& Ss(j,t-1)>0% creating
scheduled reciepts for manufacturer
                                        SRs(j,t+Ltm)=Ss(j,t-1);
                                    End
                                if Ss(j,t-1)+sum(PRs(j,t:t+Lts))-POm(j,t)<=RPs(j)%creating production
orders for supplier
                                    POs(j,t)=Ms(j)-Ss(j,t);
                                    PRs(j,t+Lts)=Ms(j)-Ss(j,t);
                                end
                                end
                                end
                                start_week=end_week+1;
                                end_week=end_week+6;
                                end
                                t=1;
                                for j=1:3
                                    for t=1:52

```

```

        if Sm(j,t)>0&k1m(j,t)>0
            Im(j)=Im(j)+Sm(j,t)+(k1m(j,t)*Qm(j));
            Is(j)=Is(j)+Ss(j,t);
        end
        if Sm(j,t)>0&k1m(j,t)<=0
            Im(j)=Im(j)+Sm(j,t);
            Is(j)=Is(j)+Ss(j,t);
        end
    end
    Imavg(j)=Im(j)/52;
    Isavg(j)=Is(j)/52;
    POM(j)=ceil(sum(POm(j,1:52)/52))
    POS(j)=ceil(sum(POM(j,1:52)/52))
    DM(j)=sum(Dmj(j,1:52));
    NBm(j)=ceil(sum(BOm(j,1:52))/52);
    Cm(j)=(Km(j)/hm(j))*POM(j)+(NBm(j)*BH) + Imavg(j)
    Cs(j)=(Ks(j)/hs(j))*POS(j)+Isavg(j);
    C(j)=Cm(j)+Cs(j);
end
CT=sum(C(1,1:3));
BO=sum(NBm(1,1:3));
DT=sum(D(1,1:3));
SL=1-(BO/DT);
%Flexibility index
Alpha(c,x)=(SL/CT)*100;
end

```

Decoupling point

1. Make-to-Stock

```

for x=1:30
    n=5; %Number of products
    HM=1;
    for i=1:n
        var(1,i)=D(1,i)^2*.1*.1;
    end
    Vd=var;%variation in demand
    SDd=sqrt(Vd) %std deviation for distributor
    start_week=2;
    week_inc=6;
    end_week=6;
    total_weeks=54;
    Ltd=1; % lead time for distributor
    Lta=1;
    Ltm=1;
    Lts=1;
    SLm=.99 %service level for retailer
    SLd=.99 %service level for distributor
    BOM=2
    Km=[ 50 50 50];
    hm=[ 1 1 1];
    for i=1:n %no of products

```

```

        Qd(i)=round( sqrt(2*D(i)*50*KFGHG)); %economic order qty
for distributor
    SSd(i)=round(SDd(i)*SLd); %safety stock for distributor
    RPd(i)=round(SSd(i)+(Lta+Ltm)*D(i)); %reorder point for
distributor
    Md(i)=round(Qd(i)+RPd(i)); %maweeek_inc lvl of inv for
distributor
end
    dmj=BOM*[(sum(D(1,1:n))) (sum(D(1,1:n))) D(1,1:n) ];%BOM
explosion
    Vmj=BOM*[(sum(Vd(1,1:n))) (sum(Vd(1,1:n))) Vd(1,1:n) ];
    SDm=sqrt(Vmj);
    for j=1:3 %no of raw materials/components
        Qm(j)=round(sqrt(2*dmj(j)*52*Km(j)/hm(j))); %economic order
qty for manufacturer
        SSm(j)=round(SDm(j)*SLm); %safety stock for manufacturer
        RPs(j)=dmj(j)*Lts + SSm(j);
        Mm(j)=(Qm(j)+RPs(j))
        %RPs(j)=sum(RPd(1,1:4));
        %Mm(j)=sum(Md(1,1:4)); %maweeek_inc lvl of inv for
manufacturer
    end
    SDmj= round(sqrt(Vmj));
    Sm=zeros(3,total_weeks);
    SRa=zeros(n,total_weeks +Ltd+Lta+Ltm+Lts);
    SRd=zeros(n,total_weeks +Ltd+Lta+Ltm+Lts);
    BOD=zeros(n,total_weeks);
    Sd=zeros(n,total_weeks); % stock at distributor
    SRm=zeros(n,total_weeks +Ltd+Lta+Ltm+Lts);% scheduled receipts
by manufacturer
    Dd=zeros(n,total_weeks+Lta+Ltm);
    POD=zeros(n,total_weeks+Ltd+Lta+Ltm+Lts);
    Im=zeros(3,1);
    Id=zeros(n,1);
    Nm=zeros(3,1);
    Nd=zeros(n,1);
    for i=1:n%real demand for distributor

Dd(i,:)=abs(round(D(i)+SDd(i)*randn(total_weeks+Lta+Ltm,1)));
    end
    for week=1:9
        for t=start_week:end_week
            for i=1:n%calculating the stock for distributor
                Sd(i,1)=Md(i)-Dd(i,1);
                if Sd(i,1)<=RPd(i)
                    POD(i,1)=Md(i)-Sd(i,1);
                    SRd(i,1+Ltm+Ltd)=Md(i)-Sd(i,1);
                end
                Sd(i,t)= Sd(i,t-1) + SRa(i,t)-Dd(i,t);
            if Sd(i,t-1)+sum(SRD(i,t:t+Lta+Ltm))-Dd(i,t)<=RPd(i)
                POD(i,t)=Md(i)-Sd(i,t);
                SRd(i,t+Ltm+Lta)=POD(i,t);
                Nd(i)=Nd(i)+1;
            end
            if Sd(i,t)<0 & Sd(i,t-1)<0% Create back orders
                BOD(i,t)=abs(Sd(i,t));
            end
        end
    end
end

```

```

        if Sd(i,t)<0 &Sd(i,t-1)<0% Create back orders
            BOd(i,t)=abs(Sd(i,t-1)-Sd(i,t));
        end
    end
    for j=1:3%calculating the stock for
manufacturer/assembler
        Sm(j,1)=Mm(j)-sum(POd(1:n,1))*BOM;
        SRa(1,1+Ltm+Lta)=POd(1,1);
        SRa(2,1+Ltm+Lta)=POd(2,1);
        SRa(3,1+Ltm+Lta)=POd(3,1);
        SRa(4,1+Ltm+Lta)=POd(4,1);
        SRa(5,1+Ltm+Lta)=POd(5,1);
        if Sm(j,t)>=0
            SRa(1,t+Ltm+Lta)=POd(1,t);
            SRa(2,t+Ltm+Lta)=POd(2,t);
            SRa(3,t+Ltm+Lta)=POd(3,t);
            SRa(4,t+Ltm+Lta)=POd(4,t);
            SRa(5,t+Ltm+Lta)=POd(5,t);
        end
        if Sm(j,t)<0&Sm(j,t-1)>0
            D_temp=POd;
            %-----
            for k=1:n
                [val,I]=min(D_temp(:,t));
                D_temp(I,t)=max(POd(:,t));
                if Sm(j,t-1)+SRm(j,t)+SB(j,t)>=POd(I,t)*BOM
                    Sm(j,t)=Sm(j,t-1)+SRm(j,t)+SB(j,t)-
POd(I,t)*BOM;
                    SRa(I,t+Lta+Ltm)=POd(I,t);
                Else
if Sm(j,t-1)+sum(SRm(j,t:t+Lts))+SB(j,t)<POd(I,t)*BOM
                    SRa(I,t+Lta+Ltm)=floor((Sm(j,t-1)+SRm(j,t)+SB(j,t))/BOM);
                end
            end
        end
        end
        %-----
        Sm(j,t)= Sm(j,t-1)+ SRm(j,t)-sum(POd(1:n,t))*BOM;
if (Sm(j,t-1)+sum(SRm(j,t:t+Lts))-sum(POd(1:n,t))*BOM<=Rpm(j))
            Pom(j,t)=Mm(j)-Sm(j,t);
            SRm(j,t+Lts)=Pom(j,t);
            Nm(j)=Nm(j)+1
        end
    end
end
end
start_week=end_week+1;
end_week=end_week+6;
end
t=1;
for i=1:n
    NBd(i,1)=ceil((sum(BOd(i,1:52)))/52)
    NB(i,1)=((sum(BOd(i,1:52))))
    Demand(i,1)=sum(Dd(i,1:52))
    for t=1:52
        if Sd(i,t)>0
            Id(i,1)=Id(i,1)+ Sd(i,t);
        end
    end
end

```

```

end
Idavg(i,1)=Id(i,1)/52;
mn(i,1)=(sum(POd(i,1:52))/52)

Cd(i,1)=Idavg(i,1)+KFGHFG*((sum(POd(i,1:52))/52)+Md(i)/52)+sum(NBd(i,1))
*BH(i)
end
mnt=sum(mn(1:n,1))
for j=1:3
    for t=1:52
        if Sm(j,t)>0
            Im(j,1)=Im(j,1)+Sm(j,t);
        end
    end
    Imavg(j)=Im(j)/52;
    Cm(1,j)=(KrawHFG*mnt)+ Imavg(j)*(hrawHFG)
end
CmWIP=Ltm*((sum(POd(i,1:52))/52))*HmHFG1
CaWIP=Lta*((sum(POd(i,1:52))/52))*HaHFG1
DT=sum(Demand(1:n,1));
CD=sum(Cd(1:n,1))
CM=sum(Cm(1,1:3));
CT=CM+CD+CmWIP+CaWIP;
BO=sum(NB(1:n,1));
SL=1-(BO/DT);
Alpha(c,x)=(SL/CT)*100;
end
Alpha1(c,1)=sum(Alpha(c,1:x))/x;

```

2. Assemble-to-Order

```

for x=1:30
    n=5; %Number of products
    HM=1;
    for i=1:n
        var(1,i)=D(1,i)^2*.1*.1;
    end
    Vd=var;%variation in demand
    SDD=sqrt(Vd);
    SDA=sqrt(sum(Vd(1,1:n))) %std deviation for distributor
    start_week=2;
    week_inc=6;
    end_week=6;
    total_weeks=54;
    Ltd=1; % lead time for distributor
    Lta=1;
    Ltm=1;
    Lts=1;
    SLm=.99 %service level for retailer
    SLa=.99 %service level for distributor
    BOM=2

```

```

Ia=0;
Km=[ 50 50 50];
hm=[ 1 1 1];
Kmh=KmHFG1/HmHFG1
% WIP stock
Qa=round( sqrt(2*sum(D(1:n))*50*Kmh)); %economic order qty for
distributor
SSa=round(SDa*SLa); %safety stock for distributor
RPa=round(SSa+(Ltm*sum(D(1:n)))); %reorder point for
distributor
Ma=round(Qa+RPa); %maweeek_inc lvl of inv for distributor

dmj=BOM*[(sum(D(1,1:n))) (sum(D(1,1:n))) sum(D(1,1:n))];%BOM
explosion
Vmj=BOM*[(sum(Vd(1,1:n))) (sum(Vd(1,1:n))) (sum(Vd(1,1:n)))];
SDm=sqrt(Vmj);
for j=1:3 %no of raw materials/components
Qm(j)=round(sqrt(2*dmj(j)*52*Km(j)/hm(j))); %economic order
qty for manufacturer
SSm(j)=round(SDm(j)*SLm); %safety stock for manufacturer
RPm(j)=dmj(j)*Lts + SSm(j);
Mm(j)=Qm(j)+RPm(j)
%RPm(j)=sum(RPd(1,1:4));
%Mm(j)=sum(Md(1,1:4)); %maweeek_inc lvl of inv for
manufacturer
end
SDmj= round(sqrt(Vmj));
Sm=zeros(3,total_weeks);
SRA=zeros(n,total_weeks +Ltd+Lta+Ltm+Lts);
SRd=zeros(n,total_weeks +Ltd+Lta+Ltm+Lts);
BOR=zeros(n,total_weeks);
Sd=zeros(n,total_weeks); % stock at distributor
SRm=zeros(n,total_weeks +Ltd+Lta+Ltm+Lts);% scheduled receipts
by manufacturer
SB=zeros(n,total_weeks +Ltd+Lta+Ltm+Lts);
Dd=zeros(n,total_weeks+Lta+Ltm);
POa=zeros(n,total_weeks+Ltd+Lta+Ltm+Lts);
POm=zeros(n,total_weeks+Ltd+Lta+Ltm+Lts);
POd=zeros(n,total_weeks+Ltd+Lta+Ltm+Lts);
BOD=zeros(n,total_weeks+Ltd+Lta+Ltm+Lts);
Im=zeros(3,1);
Id=zeros(n,1);
Nm=zeros(3,1);
Nd=zeros(n,1);
for i=1:n%real demand for distributor

Dd(i,:)=abs(round(D(i)+SDd(i)*randn(total_weeks+Lta+Ltm,1)));
end
for week=1:9
for t=start_week:end_week
%calculating the stock at assembler
Sa(1,1)=Ma(1,1)-sum(Dd(1:n,1));
if Sa(1,1)<=RPa
Pod(1,1)=Ma-Sa(1,1);
SRa(i,1+Ltm)=Ma-Sa(1,1);
SRd(1,1+Ltd)=Dd(1,1)
SRd(2,1+Ltd)=Dd(2,1)

```

```

        SRd(3,1+Ltd)=Dd(3,1)
        SRd(4,1+Ltd)=Dd(4,1)
        SRd(5,1+Ltd)=Dd(5,1)
    end
    Sa(1,t)=Sa(1,t-1)+SRm(1,t)-sum(Dd(1:n,t));
    if Sa(1,t)>=0
        SRd(1,t+Ltd)=Dd(1,t)
        SRd(2,t+Ltd)=Dd(2,t)
        SRd(3,t+Ltd)=Dd(3,t)
        SRd(4,t+Ltd)=Dd(4,t)
        SRd(5,t+Ltd)=Dd(5,t)
    end
    end
    if Sa(1,t-1)+sum(SRa(1,t:t+Lta+Ltm))-
sum(Dd(1:n,t))<=RPa(1,1)
        POa(1,t)=Ma(1,1)-Sa(1,t);
        SRa(1,t+Ltm)=POd(1,t);
        Nd=Nd+1;
    end
    D_temp=Dd;
    if Sa(1,t)<0&Sa(1,t-1)>0
        Dtemp=Dd;
        for k=1:n
            [val,I]=min(D_temp(:,t));
            D_temp(I,t)=max(Dd(:,t));

            if Sa(1,t-1)+SRm(1,t)+SB(1,t)>=Dd(I,t)
                Sa(1,t)=Sa(1,t-1)+SRm(1,t)+SB(1,t)-Dd(I,t);
                SRd(I,t+Ltm)=Dd(I,t);
            Else
                if Sa(1,t-1)+sum(SRm(1,t:t+Ltm))+SB(1,t)<Dd(I,t)
                    SRd(I,t+Lta+Ltm)=(Sa(1,t-1)+SRm(1,t)+SB(1,t));
                    BOD(I,t)=Dd(I,t)-((Sa(1,t-1)+SRm(1,t)+SB(1,t)));
                end
            end
        end
    end
    end
    for j=1:3%calculating the stock for manufacturer
        Sm(j,1)=Mm(j)-(POa(1,1))*BOM;
        SRm(1,1+Ltm)=POa(1,1);
        Sm(j,t)=Sm(j,t-1)+SRm(j,t)-POa(1,t)*BOM;
        if Sm(j,t)>=0&POa(1,t)>0
            SRa(1,t+Ltm)=POa(1,t);
        end
        if Sm(j,t)<0&Sm(j,t-1)>0
            SRa(1,t+Ltm)=floor((Sm(j,t-1)+SRm(j,t))/BOM);
        end
    end
    if (Sm(j,t-1)+sum(SRm(j,t:t+Lts))-POa(1,t)*BOM<=Rpm(j))
        POm(j,t)=Mm(j)-Sm(j,t);
        SRm(j,t+Lts)=POm(j,t);
    end
    end
    end
    start_week=end_week+1;
    end_week=end_week+6;
end
for i=1:n
    NBd(i,1)=ceil((sum(BOD(i,1:52)))/52)
end

```

```

        NB(i,1)=(sum(BOd(i,1:52)))
        Demand(i,1)=sum(Dd(i,1:52))
        Cd(i,1)=D(1,i)*KaHFG1 +NBd(i,1)*BH(i)
    end
    for j=1:3
        for t=1:52
            if Sm(j,t)>0
                Im(j,1)=Im(j,1)+Sm(j,t);
            end
        end
        Imavg(j)=Im(j)/52;
        Cm(j,1)=(KrawHFG*(sum(POm(j,1:52)))/52)+ Imavg(j)*(hrawHFG)
    end
    for t=1:52
        if Sa(1,t)>0
            Ia=Ia+Sa(1,t);
        end
    end
    Iaavg=Ia/52;
    for i=1:n
        DemandWIP(n,1)=sum(POa(n,1:52));
    end
    Dmean=floor(sum(POa(1,1:52))/52+(Ma(1,1)/52))
    Ca=Dmean*KmHFG1+ Iaavg*(HmHFG1)
    CaWIP=Lta*sum(D(1,1:n))*HaHFG1
    CmWIP=Dmean*Ltm*HmHFG1
    CD=sum(Cd(1:n,1));
    DT=sum(Dd(1:n,1));
    CM=sum(Cm(1:3,1));
    CT=CM+Ca+CaWIP+CmWIP+CD
    BO=sum(NB(1:n,1));
    SL=abs(1-(BO/DT));
    Alpha(c,x)=(SL/CT)*100;
end

```

3. Make-to-Order

```

for x=1:30
    n=5; %Number of products
    HM=1;
    for i=1:n
        var(1,i)=D(1,i)^2*.1*.1;
    end
    Vd=var;%variation in demand
    %for i=1:n
    %Kd(i)=KMHFP;
    %hd(i)=1;
    %end
    dmj=2*[(sum(D(1,1:n)) (sum(D(1,1:n))) D(1,1:n) ];%BOM
explosion
    Vmj=2*[(sum(Vd(1,1:n)) (sum(Vd(1,1:n))) Vd(1,1:n) ];
    SDmj= round(sqrt(Vmj));
    SDd=sqrt(Vd);
    start_week=2;

```



```

end_week=6;
total_weeks=54;
Ltm=1; % lead time for transportation of components from
supplier to manufacturer
Lts=1; % lead time for production of components at supplier
SLm=.99; %service level for manufacturer
SLs=.99; %service level for supplier
for j=1:3
    Qm(j)=round( sqrt(2*dmj(j)*52*Km(j))); %economic order qty
for manufacturer
    SSm(j)=round(SDmj(j)*SLm); %safety stock for manufacturer
    RPm(j)=round(SSm(j)+Lts*dmj(j)); %reorder point for
manufacturer
    Mm(j)=round(Qm(j)+RPm(j)); %maweeek_inc lvl of inv for
manufacturer
end
start_week=2;
end_week=6;
total_weeks=54;
Ltd=1; % lead time for distributor
Lta=1; % lead time for assembler
Ltm=1; % lead time for manufacturer
Lts=1; % lead time for supplier
SLd=.9 ;%service level for distributor
SLm=.9 ;%service level for manufacturer
Sr=zeros(n,total_weeks);
SRd=zeros(n,total_weeks+Ltd+Lta+Ltm);
SB=zeros(n,total_weeks+Ltd+Lta+Ltm);
BOD=zeros(n,total_weeks);
Im=zeros(n,total_weeks); % stock at distirbutor
SRm=zeros(n,total_weeks+Ltd+Lta+Ltm);% scheduled reciepts by
manufacturer
Dr=zeros(n,total_weeks+Ltd+Lta+Ltm);
POd=zeros(n,total_weeks+Ltd+Lta+Ltm);
Nm=zeros(n,1);
BOM=2;
%no of products
for i=1:n
Dd(i,:)=abs(round(D(i)+SDd(i)*randn(total_weeks+Lta+Ltm+Ltd,1)));
end
for week=1:total_weeks/6
    for t=start_week:end_week
        for j=1:3
            Sm(j,1)=Mm(j)-(sum(Dd(1,1:5)))*BOM;
            SRd(1,1+Ltm+Lta+Ltd)=Dd(1,1);
            SRd(2,1+Ltm+Lta+Ltd)=Dd(2,1);
            SRd(3,1+Ltm+Lta+Ltd)=Dd(3,1);
            SRd(4,1+Ltm+Lta+Ltd)=Dd(4,1);
            SRd(5,1+Ltm+Lta+Ltd)=Dd(5,1);
        end
        for j=1:3%calcuatlting the stock at manufacturer
            if Sm(j,1)<=RPm(j)
                POm(j,1)=Mm(j)-Sm(j,1);
                SRm(j,1+Ltm)=POm(j,1);
            End
Sm(j,t)= Sm(j,t-1)+SRm(j,t)+SB(j,t)-(sum(Dd(1:n,1)))*BOM;

```

```

    if Sm(j,t) >= 0
        SRd(1,t+Lta+Ltm+Ltd) = Dd(1,t);
        SRd(2,t+Lta+Ltm+Ltd) = Dd(2,t);
        SRd(3,t+Lta+Ltm+Ltd) = Dd(3,t);
        SRd(4,t+Lta+Ltm+Ltd) = Dd(4,t);
        SRd(5,t+Lta+Ltm+Ltd) = Dd(5,t);
    end
    if Sm(j,t) < 0 & Sm(j,t-1) > 0
        D_temp = Dd;
        %-----
        for k=1:n
            [val,I] = min(D_temp(:,t));
            D_temp(I,t) = max(Dd(:,t));
        end
    end
    if Sm(j,t-1) + SRm(j,t) + SB(j,t) >= Dd(I,t) * BOM
        Sm(j,t) = Sm(j,t-1) + SRm(j,t) + SB(j,t) - Dd(I,t) * BOM;
        SRd(I,t+Lta+Ltm+Ltd) = Dd(I,t);
    else
        if Sm(j,t-1) + SRm(j,t) + SB(j,t) < Dd(I,t) * BOM
            SRd(I,t+Lta+Ltm+Ltd) = floor( (Sm(j,t-1) + SRm(j,t) + SB(j,t)) / BOM );
            BOd(I,t) = Dd(I,t) - floor( (Sm(j,t-1) + SRm(j,t) + SB(j,t)) / BOM );
        end
    end
end
end

%-----
% SRd(j,t+Lta+Ltm+Ltd) =
% SB(i,t+Ltm+Lta+Ltd+Lts) = abs(Sm(j,t));
end
Sm(j,t) = Sm(j,t-1) + SRm(j,t) + SB(j,t) - (sum(Dd(1:n,1))) * BOM;
if Sm(j,t-1) + sum(SRm(j,t:t+Ltm)) - sum(Dd(1:5,t)) * BOM <= RPm(j)
    POm(j,t) = Mm(j) - Sm(j,t);
    SRm(j,t+Lts) = POm(j,t);
    Nm(j) = Nm(j) + 1;
end
end
end
start_week = end_week + 1;
end_week = end_week + 6;
end
t = 1;
for i = 1:n
    NBd(i,1) = ceil( (sum(BOd(i,1:52))) / 52 )
    NB(i,1) = ceil( (sum(BOd(i,1:52))) )
    Demand(i,1) = sum(Dd(i,1:52))
    Cd(i,1) = D(1,i) * KFGHFG + NBd(i,1) * BH(i)
end
CmWIP = Ltm * sum(D(1,1:n)) * HmHFG1
CaWIP = Lta * sum(D(1,1:n)) * HaHFG1
for j = 1:3
    for t = 1:52
        if Sm(j,t) > 0
            Im(j) = Im(j) + Sm(j,t);
        end
    end
end
Imavg(j) = Im(j) / 52;
Cm(1,j) = (KrawHFG * dmj(1,j)) + Imavg(j) * (hrwHFG)
end

```

```
Cm=sum(Cm(1,1:3));
CD=sum(Cd(1:n,1))
DT=sum(Demand(1:n,1));
CT=Cm+CD+CmWIP+CaWIP
BO=sum(NB(1:n,1));
SL=abs(1-(BO/DT));
Alpha(c,x)=(SL/CT)*100;
end
```

BIBLIOGRAPHY

- [1] *Next generation study*, “Collaborative effort among different groups: Agility forum, Leaders for manufacturing and technology enabling agile manufacturing,” 1997
- [2] Frickle E., and Schulz, A.P, “Design for Changeability (DFC): Principles To Enable Changes in Systems Throughout Their Entire Lifecycle,” *The Journal of The International Council of Systems Engineering*, Vol. 8, No 4, pp. 322-359
- [3] Jones R.M., Naylor B., and Towill D.R., “Lean, agile or Leagile? Matching your supply chain to the market place,” *International Journal of Production Research*, Vol. 38, No17, pp. 4061-4070
- [4] Treville S.D & Vanderhaeghe A., “How to Fail at Flexibility,” *Supply Chain Forum, An International Journal*, Vol 4, 2003
- [5] Pujawan, N., “Assessing supply chain flexibility: a conceptual framework and case study,” *International Journal of Integrated Supply Management*, 2004, Vol. 1. pp. 79-97
- [6] Swamidass P. M., Newell, W. T., “Manufacturing strategy, environmental uncertainty and performance: a path analytic model,” *Management Science*, 1987, Vol. 33, No. 4, pp -509-524
- [7] Ozgen D., Gulsun B., Biyik G., “Flexibility concept in supply chain management: A conceptual framework and overview,” *35th international conference on computers and industrial Engineering*
- [8] Duclos L. K, Vokurka R. J., Lummus R.R., “A conceptual model of supply chain Flexibility,” *Industrial Management & Data Systems*, 2003, Vol. 103, pp. 446-456
- [9] Zhang Q., Vonderembse M. A., Lim J.S., “Value chain flexibility: a dichotomy of competence and capability,” *International Journal of Production Research*, 2002, Vol. 40, pp. 561-583
- [10] Swafford P., Ghosh, S., Murthy N., “Model of Global Supply Chain Agility and its impact on competitive performance,” *The 2000 DSI Annual Conference Proceedings in Orlando*, 2000

- 1] Kumar V., Fantazy K., Kumar, U., "The implementation and management of supply chain flexibility: Conceptual framework," *ASAC*, 2004, Quebec
- 2] Slack, N. "Flexibility as a Manufacturing objective," *International Journal of Operations & Production Management*, Vol. 25, pp.1190- 2000
- 3] Suarez F.F., Cusumano M.A., and Fine C.H., "Flexibility and Performance: A Literature critique and Strategic Framework," Massachusetts Institute of Technology, Sloan School, WP# 3298-91-BPS, 1991
- 4] www.supply-chain.org, December, 2007
- 5] Christopher M., "The Agile Supply Chain competing in Volatile Markets," *Industrial Marketing Management* , Vol. 29, pp. 37-44, 2000
- 6] Tan keah C., Kannan, Vijay R., Handfield, Robert B., "Supply chain management: Supplier performance and firm performance," *International journal of purchasing and materials management*, 1996, pp. 2-9
- 7] Lee H.L., "Aligning Supply Chain Strategies with Product Uncertainties," *California Management Review*, Vol. 44, No. 3, 2002
- 8] Chung C., Chen I., "Managing the flexibility of Flexible Manufacturing Systems for competitive advantage," In M. J. Liberatore's (ed.) *Selection and Evaluation of Advanced Manufacturing Technologies*, 1990, pp. 280±305
- 9] Tuluca S., Stalinski, P., "The Manufacturing flexibility to fix products: Valuation and optimal strategy," *International journal of production economics*, Vol. 78, 2002, pp. 13-28
- 0] Correa L.H., "The flexibility of technological and human resources in automotive manufacturing," *Journal of integrated manufacturing systems*, 1994, Vol. 5, No.1, pp.33-40
- 1] Zhang Q., Vonderembse M.A., Lim J.S., "Logistics Flexibility and its impact on customer satisfaction," *The International Journal of Logistics Management*, Vol. 16., No. 1., pp. 71-95, 2005
- 2] Langley C.J, Holcomb M.C., "Creating logistics customer value," *Journal of business logistics* 3rd edn. 1992

- 23] Yang B., Burns N.D., and Backhouse C.J., "Management of uncertainty through postponement," *International Journal of Production Research*, Vol. 42, No. 6., pp. 1049-1064, 2004
- 24] Naylor J.B., Naim M.M., and Berry D., "Leagility: Integrating the lean and agile manufacturing paradigms in the total supply chain," *International Journal of Production Economics*, Vol. 62, pp. 107-118, 1999
- 25] Chopra S., and Meindl P., "Supply Chain Management: Strategy, Planning, and Operation," Second edition, 2004
- 26] Enns S.T., and Suwanruji P., "Distribution Planning and Control and Control: An Experimental Comparison of DRP and Order Point Replenishment Strategies," *Academy of Business and Administrative Sciences (ABAS) conference proceedings*, 2000
- 27] Chang Y., and Makatsoris H., "Supply Chain modeling using simulation," *International Journal of Simulation*, Vol. 2, No. 1
- 28] Umeda S., and Jain S., "Integrated Supply Chain Simulation System(ISSS)- Modeling Requirements and Design Issues," *National Institute of Standards and technology*, 2004
- 29] Kleijnen P. C. J., and Smits M.T., "Performance metrics in supply chain management," *Journal of Operations Research Society*, pp.1-8, 2003
- 0] Zhao X., Lai F., and Lee, T.S., "Evaluation of safety stock methods in multilevel material requirement planning (MRP) systems," *Production Planning and Control*, Vol. 12., No. 8, pp. 794-803, 2001
- 1] Ballou R.H., "Business Logistics Management: planning, organizing, and controlling the supply chain," Fourth Edition, 1998
- 2] Lee. L. H., and Tang S.C., "Modeling the Costs and Benefits of Delayed Product Differentiation," *Management science journal*, Vol. 43, pp. 40-53, 1997

- 3] Fisher L.M., "What is the right supply chain for your product?," *Harvard business school*, 1997
- 4] Harell C., Ghosh B., K, and Bowden R., C., "Simulation using Promodel," Second edition, 2000

VITA

Mr. Poorna Marappa was born on April 8, 1982 in the city of Bangalore, India. Poorna pursued his Bachelors degree in the Mechanical Engineering from one of the top engineering schools in India: BMS college of Engineering. During the under graduation, Poorna did projects in Volvo India Pvt. Ltd and Toyota Kirloskar where he gained practical insight and also developed an interest to pursue higher education. He graduated with a B.E. in Mechanical Engineering in May 2006. Then, he joined as a graduate student at the University of Missouri-Rolla (UMR), USA for System Engineering program in January, 2006. During his master's program he gained knowledge in system engineering and supply chain concepts. He also did a co-op with Harley Davidson Motor Company from January 2007 to April 2007, where he worked as a Supply chain analyst. He has graduated from Missouri University of Science and Technology as a Systems Engineer in May 2008.