ANALYSIS OF A TWO-ECHELON MULTI-ITEM INVENTORY SYSTEM WITH POSTPONEMENT

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ABSTRACT

ANALYSIS OF A TWO-ECHELON MULTI-ITEM INVENTORY SYSTEM WITH POSTPONEMENT

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Increased product proliferation and global competition are forcing companies within the supply chain to adopt new strategies. Postponement is an effective strategy that allows companies to be agile and cost effective in dealing with the dynamics of global supply chains. Postponement centres around delaying activities in the supply chain until real information about the market is available, which reduces the complexity and uncertainty of dealing with a proliferation of products. A two-echelon divergent supply chain entailing a central production facility and N retailers facing stochastic demand is studied within the inventory-distribution system. A periodic review order-up-to strategy is incorporated at all echelons. Unique to the study, five different systems are created and the effectiveness of several postponement strategies (form and transshipment) under various operational settings are compared. The importance of postponement under an integrated supply chain context and its contribution to various sector implementations are also discussed. Simulation is used to analyze the performance of the systems especially with respect to cost, order lead time and the effectiveness of transshipment policies. The study is unique in determining factors that favour one system implementation over another and distinguishing sector requirements that support postponement. In the study, postponement is found to be an effective strategy in dealing with managing item variety, demand uncertainty and differences in review periods in the two echelon supply chain for different experimental settings.

Keywords: Form/Logistics Postponement, Two-echelon Inventory System, Multi-item, Generic product/item

ÖZ

ERTELEMELİ ÇOK-ÜRÜNLÜ İKİ-KATMANLI ENVANTER SİSTEMİ

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Artan ürün çeşitliliği ve global rekabet, tedarik zincirinde yer alan şirketleri yeni stratejiler benimsemeleri yönünde zorlamaktadır. Ürün erteleme, dinamik ve global tedarik zincirlerinin düşük maliyetle ve çevik bir şekilde idare etmeyi ön görmektedir. Ürün ertelemede süreçler piyasadan gerçek bilgi gelene kadar ertelenir, bu da ürün çeşitliliğindeki karmaşıklık ve belirsizlikle mücadele etmeyi kolaylaştırır. Bir ana depo ve rassal talep gören N tane perakendeciyi birleştiren iki-katmanlı bir tedarik zinciri, ıraksak bir envanter sistemi olarak tasarlanmıştır. Tüm katmanlarda, periyodik gözden geçirmeli, maksimum envanter seviyeli strateji benimsenir. Çalışmanın özgün tarafı, beş değişik sistem tasarımı üzerinden ürün ertelemesinin birkaç çeşidi (form erteleme ve aktarma) farklı işletme koşullarında değerlendirilir. Aynı zamanda ürün ertelemenin tedarik zinciri yapısındaki önemi ve farklı sektör uygulamalarına katkıları tartışılır. Sistemlerin performansını maliyet, ürün çevrim zamanları ve aktarma politikaları yönünden analiz edebilmek için benzetim tekniği kullanılır. Yapılan çalışma, sistemlerin ve sektör beklentilerinin ürün ertelemede hangi faktörler dahilinde etkin olduğunu göstermesi bakımından özgündür. Çalışmada ürün erteleme, iki-katmanlı tedarik zinciri yapısında farklı deneysel koşullarda, ürün çeşitliliği, talep değişkenliği ve gözden geçirme süreleri açısından etkili bir strateji olduğu görülmüştür.

Anahtar Kelimeler: Ürün/Aktarma Erteleme, İki-katmanlı Envanter Sistemi, Çok-ürün, Temel ürün

To my parents and my brother….

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CHAPTER 1

INTRODUCTION

The need for higher efficiency and lower operational costs are forcing companies to continually search for ways to improve their operations. Since supply chain management includes an immense amount of resources, the ultimate aim is to integrate the vast number of resources at various functional levels. Postponement is an effective strategy in dealing with the demand uncertainty in supply chain management. In this study, postponement is included as a value adding transformation process for the inventory distribution problem analyzed. Postponement delays the point of commitment of work-in-process inventory (termed generic inventory in postponement literature) into finalized end products/items in order to enhance asset utilization in an uncertain environment. With the proliferation of items in the market and a plethora of customer demands, postponement is in fact a strategy to obtain more actual information about item or service specifications of the customer, in order to best define and meet customer expectations (Yang *et. al*., 2007). Accordingly, the higher the uncertainty in customer demand, the more likely companies will look for oppurtunities to select a postponement strategy. The critical problem to be resolved is thus, deciding which activities will be order-driven and customized and which activities will be forecasted and standardized.

High-value adding activities motivate industries to incorporate demand driven supply chains and utilize different forms of postponement strategy. Definitions of postponement acknowledge that variety may be added at different stages in the value chain, such as in the manufacturing facility, in a regional warehouse or at a retail outlet (Skipworth and Harrison, 2006).

The benefits of postponement are derived mainly from altering the sequence of activities or delaying the time of customization. Research indicates that postponement has the potential to reduce inventory, transportation, storage and obsolescence costs, while increasing responsiveness (Yang *et. al.*, 2005). In this study, different postponement strategies are evaluated including form postponement (customizing a common/generic item) and logistics postponement (delaying the allocation and final movement of items).

This study also aims to generalize the effectiveness of postponement strategies in various settings and tries to discover where this strategy enhances the agility of the supply chain. Agility implies that the supply chain is market and service sensitive and capable of capturing and responding to real demand by reserving capacity to cope with volatile demand (Christopher and Towill, 2000).

In various inventory-distribution problem settings, the inventory in the downstream portion of the supply chain is usually held as single or multiple items in finalized form. However, this strategy entails holding more inventories of different items in order to match supply with demand. Allowing inventories to be held as a generic item helps eliminate obsolescence as well as inventory carried that is out of demand. Within supply chains, a significant proportion of total network costs are attributed to inventory costs. Companies are facing the dilemma between holding and producing more variety. Accordingly, enhancing efficiency and cost effectiveness across all echelons are vital within a supply chain. However optimizing multi-echelon systems is a challenging task. The scope of the problem, objectives, as well as the determination of centralized versus decentralized control are also critical factors affecting the decision making process in multi-echelon supply chains.

In this study, five different systems are defined in a two-echelon inventory setting in order to illustrate the importance of postponement under varying demand conditions and experimental settings. The two-echelon system considered consists of a central production facility and a number of retailers that are fed from the production facility. Centralization is adopted within the system in order to effectively control the inventories such that inter-echelon challenges due to inventory ownership are minimized. A periodic review system is adopted for the inventory policy. The orders are reviewed at fixed intervals, and each downstream stock point issues a replenishment order to its respective upstream stock point to raise its inventory position to a predetermined level. Accordingly, performance is measured for the total supply chain rather than being restricted to individual components in the echelon.

Within the production context of the five systems, the main resupply comes from the higher level site or main production facility. The initial system consists of a typical make-to-stock company where the items are sent to the retailers in their finalized forms. As postponement capabilities are given to the retailers, the items are kept in generic form in the central production facility or upper echelon, and transformed into customized items at the succeeding retailers according to the demands faced therein in the various system settings. However, retailers in the lower echelon may not be restricted in serving distinctive customers and have the chance to provide service to various customers that request the items. If logistics postponement or transshipment is allowed, the retailers may request items from the same echelon level (other retailers), instead of requesting items from the upper echelon. Lastly, a hybrid system is analyzed, where the the retailers are allowed to hold and produce customized items in unision.

Although there are vast areas where postponement applications are common, there are no implementations that have tried to discover the feasibility and validity of postponement in different supply chain settings which makes the study unique. In addition to the reference settings, various sector implementations are researched in order to derive sector-based observations as well as common settings for postponement implementations. An important contribution of the study is that it tries to define operating conditions for five different systems utilizing postponement for better inventory and resource allocation.

In short, the primary objective of this study is to determine how beneficial postponement (form and logistics) would be under a variety of operating conditions and according to the performance measures of various sector requirements. The study's primary concern is systemwide cost minimization and increased service level attainment for the customers. The dynamic nature of the supply chain is studied through simulation modelling. Simulation approach is chosen, because it leverages the strength to model stochastic elements within the supply chain structure and better models uncertainty inherent in the supply chain. Overall, 216 experimental design settings have been created to distinguish the operating characteristics of the five system implementations and the contribution of a postponement strategy in all of the implementations. The study has shown that utilizing postponement, especially form and logistics postponement at the same time, helps to reduce average total cost, while improving critical customer service measures such as the average order lead time and average fill rate. The study has also distinguished the importance of altering factor levels and their effects on all five system implementations. Postponement has been found to be an effective strategy in dealing with managing item variety, demand uncertainty and differences in review periods in the two echelons for different experimental settings.

The next chapter gives a brief description of the systems analyzed in this study. Chapter 3 gives a literature review of the topics relevant to this work. Chapter 4 introduces the general terminology and describes the functioning of the systems in an analytical context. Chapter 5 summarizes the work done in constructing the simulation model and describes how the simulation models are validated and verified. Chapter 6 describes the experimental settings and results of the study. Finally in Chapter 7, the study is concluded and suggestions for future research are given.

CHAPTER 2

PROBLEM DEFINITION AND SCOPE OF THE STUDY

The system under study is a two-echelon arborescent supply chain which utilizes a centralized periodic inventory system. Periodic review systems are common in use and are frequently used especially when items are ordered from the same supplier or require resource sharing as mentioned by Silver *et. al.* (1998). The supply chain includes a central production facility and *N* retailers respectively. The central production facility receives raw materials from an external supplier with unlimited material supply. This is a tenable strategy as many firms prefer to rely on a single dependable source for order commitment. Upon receipt of the materials, the materials are converted to a generic or common item. From this generic item, items/products may be customized into *M* different items as requested by the customer. Item customization is defined as the extension of options and characteristics of an item. A high customization potential for an item implies that there are many possible configurations possible from a common or generic item (Waller *et. al.*, 2000). Overall, there is one-to-one correspondence in the manufacturing of the item. For example, one unit of raw material produces a single unit of generic item, which is enough to convert to a single customized item. The general approach in the conversion of raw material to customized items can be viewed in Figure 2.1.

Due to volatile market conditions, there is greater risk of obsolescence and higher holding costs for the variety of items offered but not requested by the customer. Postponement allows companies to better manage demand forecasts, by delaying operations on items with attributes highly sensitive to market fluctuations. For example, in the textile industry examples of such attributes are size, color and fabric depending on customer preferences. Customization adds value to the item and reduces the chance of committing the wrong item to the wrong customer.

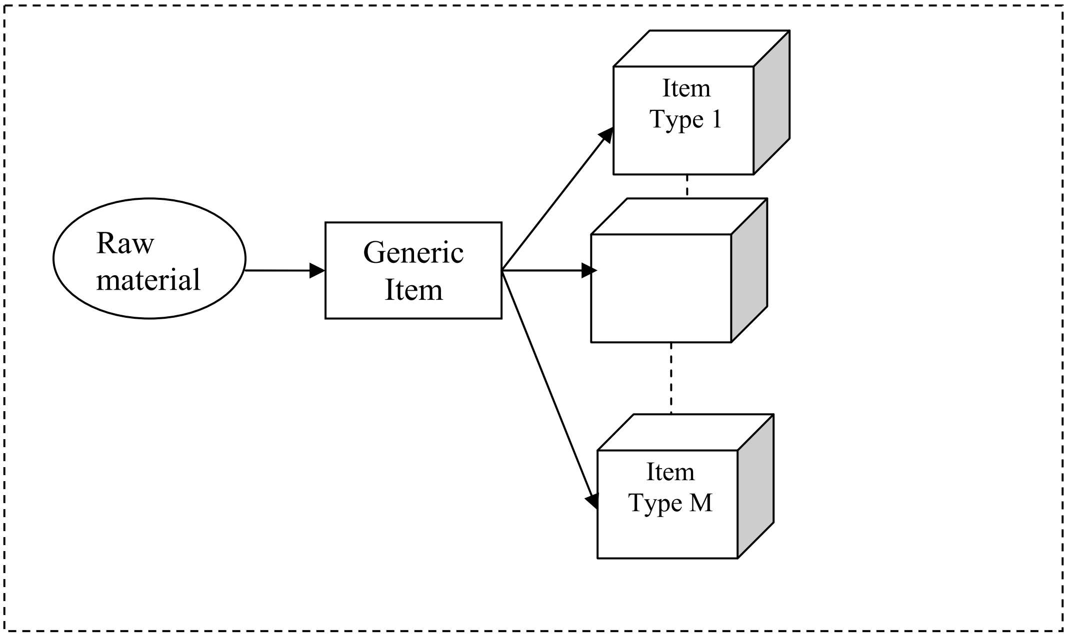

Figure 2.1 Representation of raw material conversion from generic item to customized item

In order to decrease the mismatch between company offerings and customer requests, global decision makers should ensure proper alignment across supply chain actors. A unique example is avoiding the use of classical warehousing where non-value added functionalities are eliminated. Instead, facilities or retailers are turned into advanced fulfillment centers, where customizations of goods are performed closer to the consumer or point of consumption (Pratts *et. al*., 2003). In our study we will utilize this important role and give extra capabilities to the retailers that we have defined. Specifically, we are concerned with a single supply-multiple demand location problem which is defined as a system with one depot (central production facility) that supplies multiple geographically scattered customers (retailers) in the context of integrated analysis.

Use of multiple types of postponement for potential performance enhancements have been illustrated by several authors including Rabinovich and Evers (2003) and Tibben-Lembke and Bassok (2005). However, none have detailed operating characteristics for various settings which influence the feasibility of postponement and its relevance to supply chain operating dynamics.

The sequence of events within the systems defined maybe illustrated using Figure 2.2 as adapted from the work of Rappold and Muckstadt (2000). Overall, retailers face direct demands of the customers and are responsible in satisfying their requests. Customers are not allowed to fulfill their item requests from the central production facility. Overall, the main components of the two-echelon supply chain, which is the core for the five systems and the general flow of operations, can be viewed in Figure 2.3.

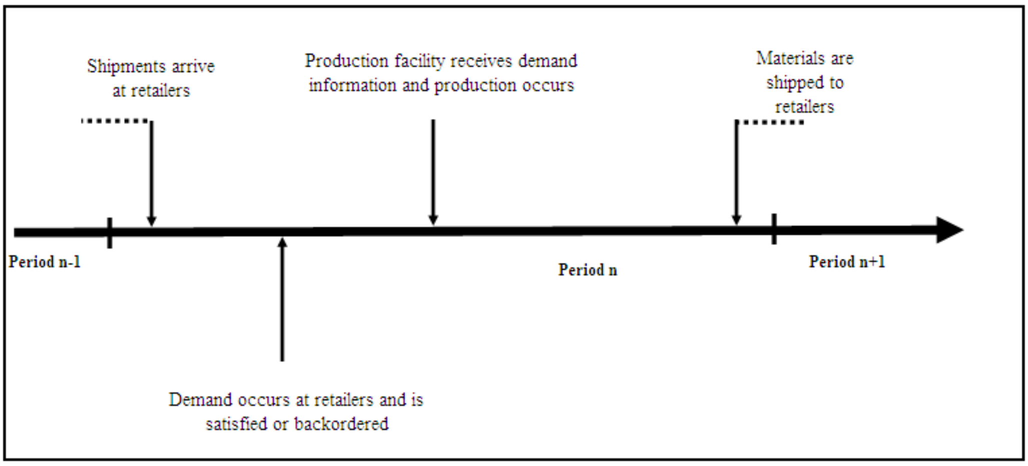

Figure 2.2 Timeline of the events occuring in the system

In multi-stage systems the items being manufactured can be inventoried at various stages of completion. The primary concern is to determine what inventories are to be manufactured and kept at the various stages and determining the inventory policy that best controls and minimizes the stock at each stage. The aim is to find global strategies that satisfy all elements in the system under common performance measures. By allowing generic items to be held at the retailers, items can be converted to the exact item requested by the customer without loss of value or extra cost on the supplier. This strategy maybe termed a lean and agile strategy

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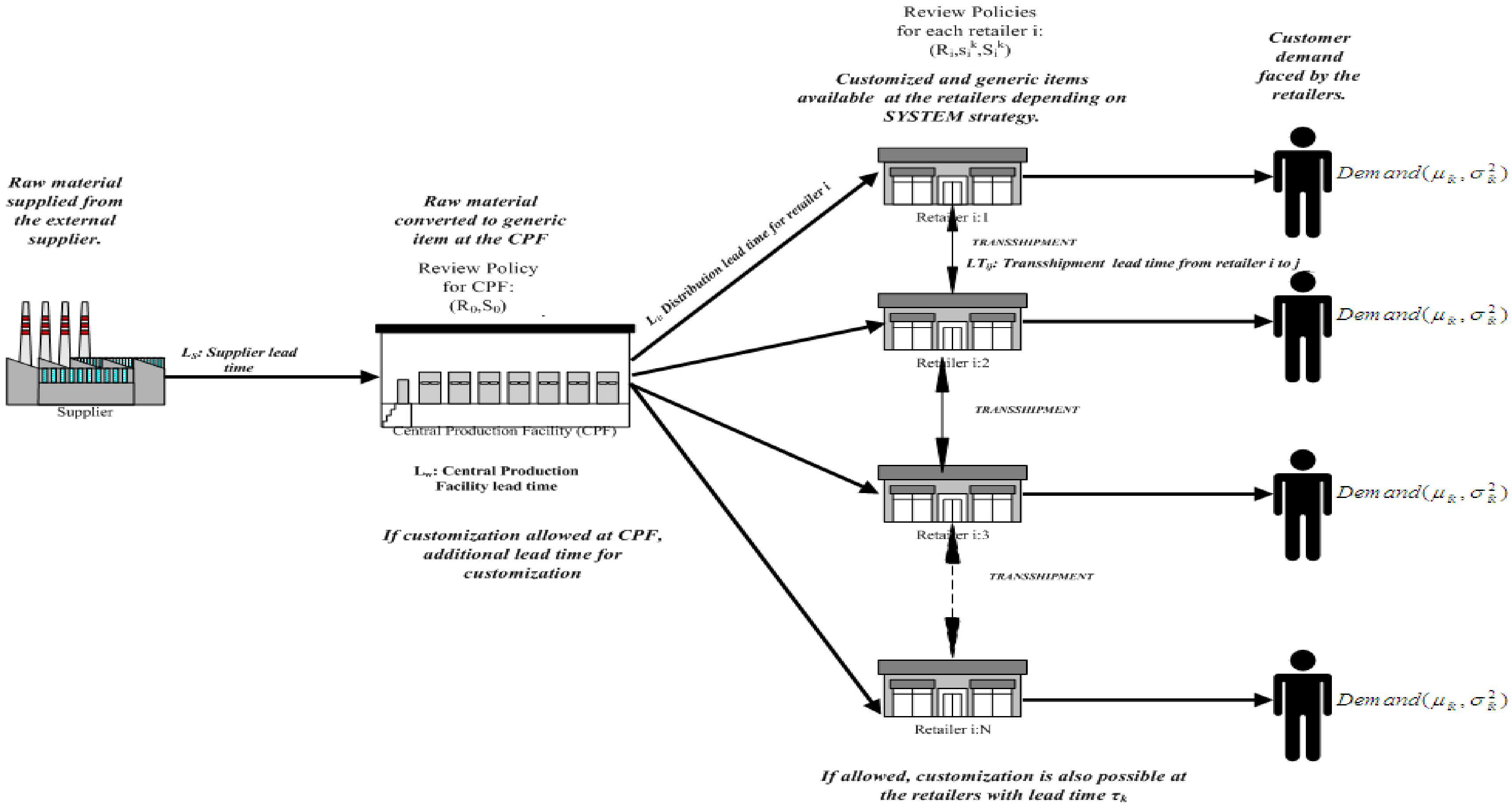

Figure 2.3 Representation of the Supply Chain Structure

for the supply chain structure utilizing postponement. Lean implies fewer resources that are wasted and agility implies fast and accurate response to the time of customer demands. The systems created help to differentiate the trade-off between holding more inventories and decreasing costs. The location (central production facility and/or retailers) of holding and processing work in process inventory is also critical in our assessment. The implications of utilizing a strategy with generic and/or customized items are aslo deal with in the respective systems in the study.

As seen in Figure 2.2 there are unique lead times associated within the system. These are supplier lead time (lead time to replenish raw material from the supplier to the central production facility), central production facility lead time (lead time to convert raw materials into generic and then to customized items as requested), transshipment lead time (lead time to carry items among the retailers at the same echelon), distribution lead time (lead time to carry items from the central production facility to the retailers) and customization lead time (the time to customize an item at a retailer/central production facility). An important factor that enhances postponement is timing. If the customization time is too long, customers might not be willing to wait for the items. In order to evaluate the contribution of utilizing form and logistics postponement, five different systems have been developed to observe the benefits that can be gained under different operational settings.

2.1 Explanation of system characteristics

The five systems are explained with respect to their unique system system characteristics and their distinction to other sytem implementations.

2.1.1 System 1: Basic System

This system is an example of a typical make-to-stock implementation. Value adding processes are carried out at the central production facility where raw material is converted to finalized items. Retailers directly request items from the central production facility. If the item is not available, the sale is backordered. The duration of customer order lead time is dependent on availability of pipeline inventory or the proximity of the next replenishment instance. Examples to such type of configurations include retail stores which provide a variety of items. If a certain chocolate manufacturer is to send an item to the retailer, it sends a variety of items for the same brand of chocolate such as plain, hazelnuts and pistachios. The consumer is not allowed to substitute the item for any other similar item as this alternative comes with a different cost. For example a plain chocolate is usually much cheaper than one including different kinds of nuts. If the consumer finds the requested item, then demand is properly satisfied. Otherwise, the customer has to wait for the recieval of the new items to the store. However, consumers are not willing to wait long enough especially for functional or commodity items, thus sale is often lost.

The general structure of the system is viewed in Figure 2.4. Common system characteristics for this system are as follows:

a) Central production facility converts raw materials into customized items based on the previous orders from the retailers. Central production facility functions as a make-to-stock system.
b) Retailers request items from the central production facility which in turn sends the requested item if available, else rations the available inventory.
c) Postponement is not allowed at the retailers.
d) Retailers hold only customized end items. If a particular item is not available, substitution among available items is not allowed.
e) Transshipment is not allowed among the retailers.

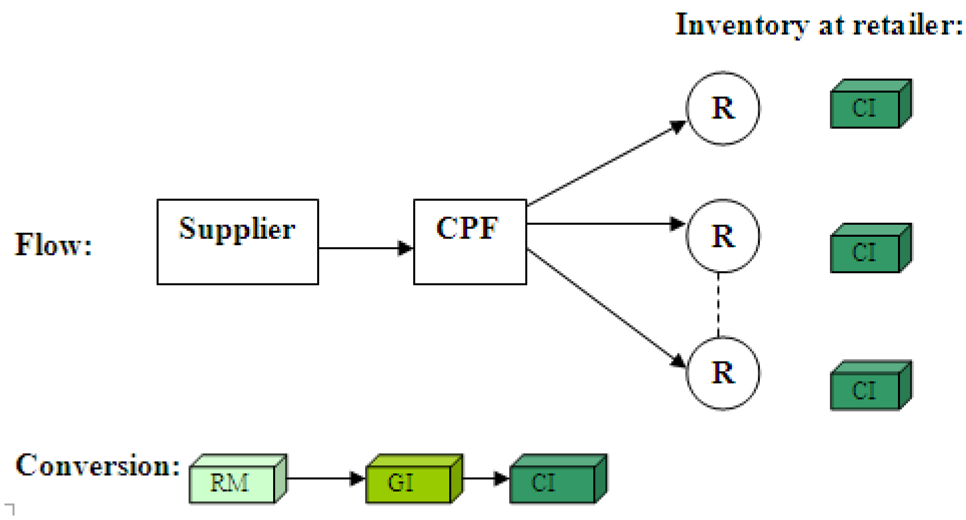

Figure 2.4 System 1 implementation

2.1.2 System 2: Basic System and Transshipment

In the second system all operations are similar to the first system. Unique to the implementation, if a specific item at a certain retailer is not available, demand is allowed to be satisfied through a logistics postponement (transshipment) policy. Transshipment or logistics postponement is the flow of items from retailer i to j, in case of impending (preventive transshipment) or actual shortage (emergency transshipment). If there is excess stock among the retailers, accordingly it maybe transshipped from the retailer with excess items to the retailer that is facing shortage or is expected to face shortage. Transshipment saves time and is an effective means to compensate for stock imbalances as it may allow the balanced distribution of inventory within the system by pooling the risk of inventory at several retailers. This possible flow of customized items in the system is depicted in Figure 2.5.

Common characteristics of the system are as follows:

a) Attributes (a)-(d) listed in System 1 are common.
b) Transshipment is allowed among the retailers. Instead of waiting for the

replenishment cycle or pipeline inventory, retailers may satisfy request from the same echelon.

c) Proximity of the retailers determines the amount of time the customer waits for replenishment from any of the retailers.

d) Transshipment maybe carried out by neighbour retailers or those that are far away. Choice of retailer to tranship items is dependent on retailer inventory availability and distance concerns.

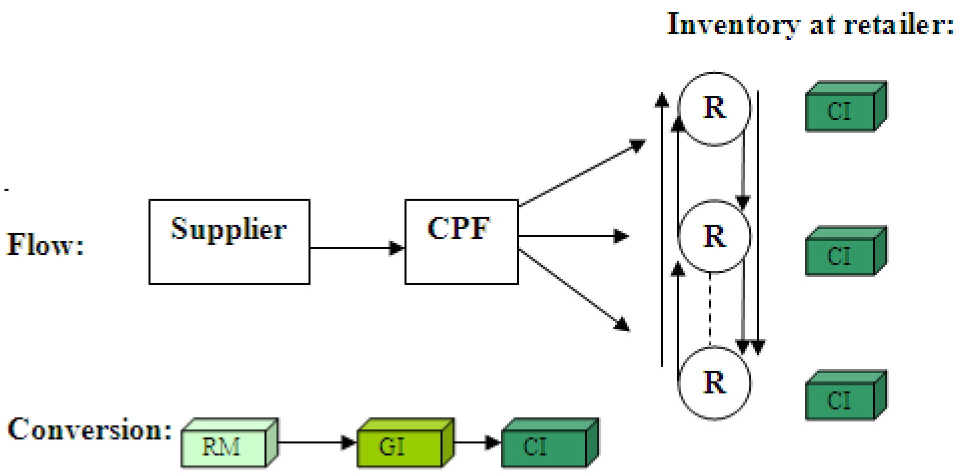

Figure 2.5 System 2 implementation

When retailers resort to transshipment, the transshipment lead-timeis assumed to be shorter than the regular replenishment lead time. An example to such a system implementation is the clothes stores at varying locations in a district. In the ready-to-wear sector many different varieties are common for the same item due to size and color variations. If the item is not available at the retailer, the item is brought from a different store in the qualifications required by the customer. The duration of backorder is also critical in system assessment. For example, a customer waiting for several minutes should not be treated like a customer waiting for several hours.

2.1.3 System 3: Postponement

In System 3, retailers have got the capacity to convert generic items received from the central production facility into customized items as requested by customers. This is termed form postponement, where the finalization of item characteristics are delayed until demand information is available to the retailers. The production facility sends generic items to retailers before demand for distinctive items are realized. Products (items) are accordingly converted to customized items after demand realization at the retailers as seen in Figure 2.6.

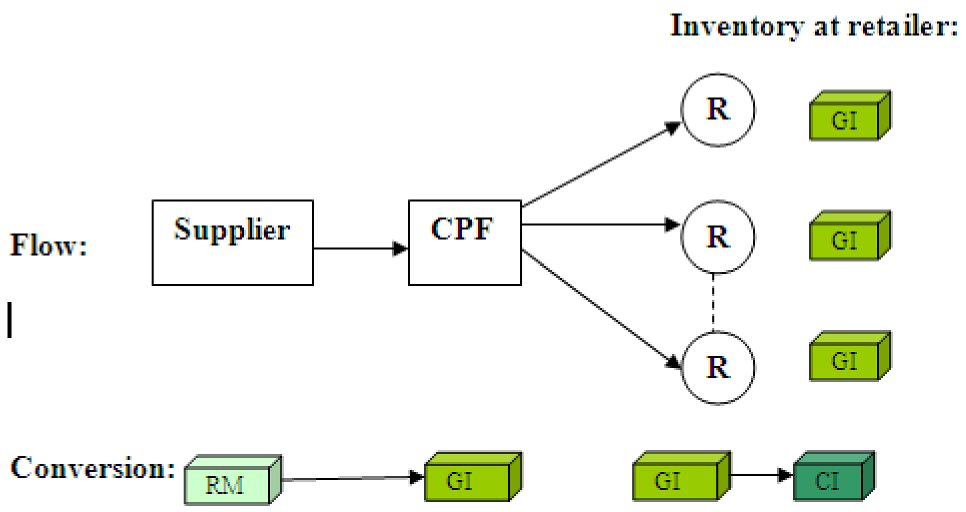

Figure 2.6 System 3 implementation

Common characteristics of the system are as follows:

a) Central production facility converts only raw material into generic item. No customized item is held at this facility. Generic item is supplied to the retailers.
b) Generic item requests at the retailer are a function of customized item requirements. One unit of customized item utilizes one generic item for conversion.

c) Retailers are given the capacity to convert generic (common) items into distinctive items as requested by the customers.
d) Retailers and central production facility only holds generic items.
e) Retailers are not allowed any transshipment among each other in the same echelon.

Retailers satisfy customer requests according to available generic inventory and are not restricted to available true customized items.

2.1.4 System 4: Postponement and Transshipment

The difference between System 3 and System 4 is the fact that logistics postponement or transshipment is allowed for generic items available at the respective retailers. System characteristics are summarized as follows:

a) Attributes (a)-(d) listed in System 3 are common.
b) Attributes (b)-(d) listed in System 2 are common.
c) Different from System 2, transshipment of generic items are carried out. Likelihood of transshipment is not a function of item type but available generic inventory.

Generic items are transshipped from any of the retailers and are sent to the retailers facing actual or imminent stockout. In comparison to System 2, as seen in Figure 2.7, items are more likely to be exchanged between retailers because there is no constraint on the type of item to be exchanged. In this system, since the item exchanged is generic, it may serve any of the specific demand requests of the customer creating an agile strategy for the supply chain.

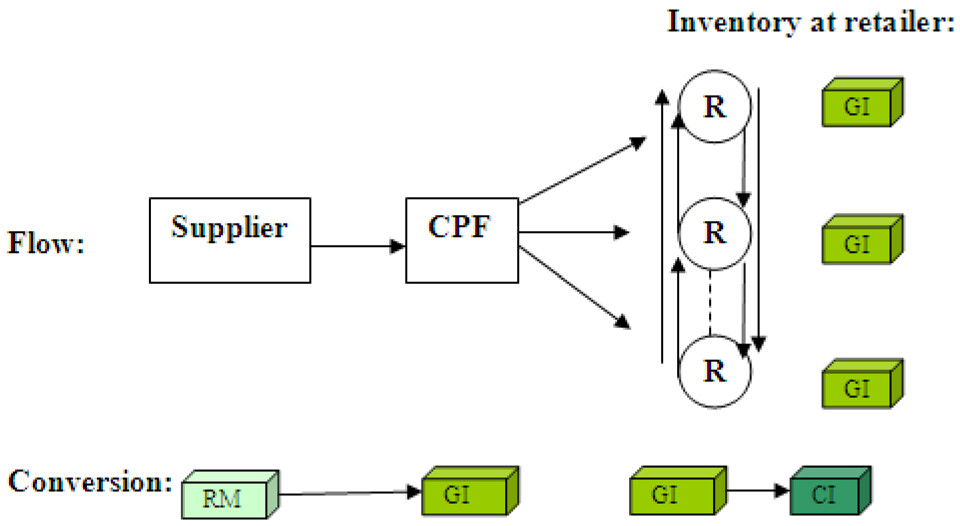

Figure 2.7 System 4 implementation

2.1.5 System 5: Hybrid system

In this system, the central production facility may allocate a predetermined capacity to generic or customized items. In this system, some items are held as generic items, whereas some are held as customized items in both the central production facility and the retailers. The retailers still have the capacity to add value through customization as well as transshipment, but for a restricted amount of total generic inventory. This is referenced as a hybrid postponement strategy where a portion of selected items are allowed postponement and are utilized for application, whereas others are customized as usual in the central production facility. This is often termed ‘capacitated’ postponement or ‘partial’ fulfillment in postponement literature due to the fact that, available capacity at the premises is not solely allocated to postponement activities. A portion of the inventory is make-to-stock and a predetermined portion of inventory is make-to-order with respect to demand realization (Graman and Magazine, 2006).

The main operating characteristics of the system are thus summarized as follows:

a) Central production facility allocates a specific capacity for customized item production, as well as resumes generic item production.
b) Central production facility sends a 'basket' of items to the retailers, where the retailer may request both generic as well as customized items. In previous systems this was not allowed.
c) Central production facility and retailers are allowed to hold generic and customized items.
d) Retailers have the capacity to customize items Customized items are make-to-stock; generic items are handled as make-to-order.
e) Transshipment at the retailers is allowed. Transshipment maybe carried out for generic and/or customized items.
f) If generic item is transshipped, accordingly it is customized at the retailer which has requested the item.

Figure 2.8 shows the flow of operations within the central production facility and retailers respectively.

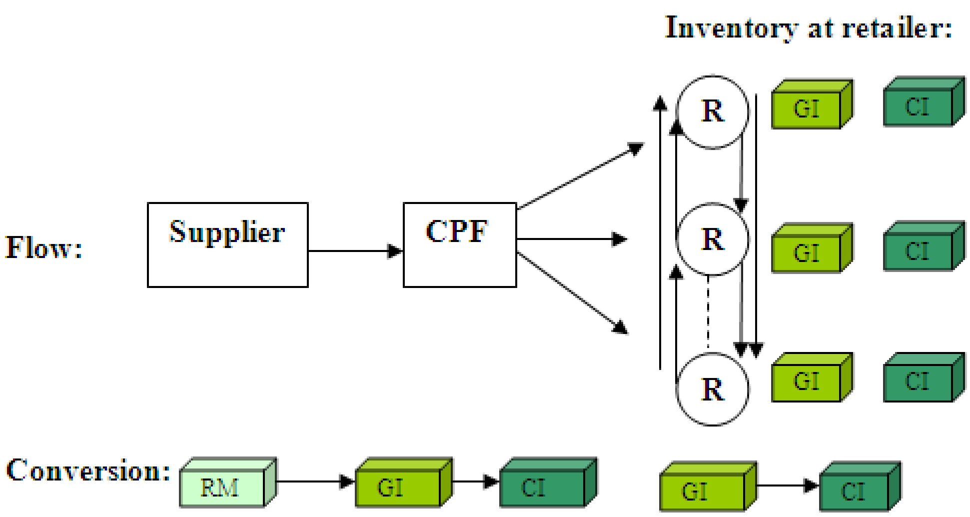

Figure 2.8 System 5 implementation

When materials are kept undifferentiated, there is a greater likelihoo the retailer can satisfy the customer's true request, which creates operational flexibility within the supply chain. The retailers have similar customization capacities but may face different demand rates. This may create a distinction in prioritizing certain high demand items faced by the retailer. Thus, the critical decision is deciding on which activities are order-driven and customized and how much of the activities are forecasted (planned) and standardized.

2.2 Evaluation of Systems

Supply chain modelling taxonomy is divided into four distinctive categories by Min and Zhou (2002). These include a) deterministic b) stochastic c) hybrid and d) IT driven models. Our system falls into the hybrid category carrying elements of both deterministic and stochastic models, as they deal with both certain and uncertain model parameters. Wyland *et. al.* (2000) point out that simulation has gained popularity as a tool used to address a range of issues in operations management and supply chain analysis due to its strength in predicting system variation and interdependencies. Thus, simulation is utilized in analyzing the previously defined systems and their uncertainties including demand, lead time and resource utilization uncertainties.

Lastly, an important part of systems assessment is the performance measures defined to measue and control operations. Performance measurement is defined as 'the process of quantifying the effectiveness and efficiency of action'. Lambert and Pohlen (2001) note that metrics are needed to remain competitive and to differentiate item and service offerings of the distinctive company. Resource measures indicate the level of efficiency in the system. Output measures aim at measuring and attaining high level of customer service. Accordingly, the following performance measures will be observed in the systems to support customer satisfaction and reduce overall costs in the system. Through experimental settings the distinctive interdependencies of model parameters and metrics will be analyzed. Moreover, the measures will assist in determining the ideal conditions when postponement strategies can be implemented.

The performance measures in our experimentation include:

Resource measures:

- Average total cost of supply chain comprising the cost for retailers and the central production facility. Costs to distribute, order, hold, customize and transship generic/customized items are included. Unnecessary inventory held is reflected as holding cost, similarly not carrying enough or the correct inventory is reflected through the backorder costs incurred in cases of shortage.

Output measures:

- Customer order lead times.
- Percentage of on-time deliveries, as a percentage of backordered items at the retailers.
- Fill-rate at the retailers.
- Quantity of transshipped items at the retailers.

These measures will help determine if there are certain incentives to hold generic items and customized items within the respective echelons. Similarly, the ideal conditions of adopting postponement strategies in accordance with previous sector studies conducted in literature will also be investigated to support the study. Previous studies have usually dealt with a specific sector and its common postponement applications, however no study has generalized the implementation of postponement within a cross-sector and supply chain context which makes our study unique and value-adding in literature.

CHAPTER 3

LITERATURE REVIEW

3.1 Postponement and the Supply Chain

A supply chain is a network entailing suppliers, manufacturers, distributors, retailers and customers. Supply chain management has gained increased attention within both industry and academic work. Mikkola and Larsen (2004) have attributed this interest to several factors including the emergence of flexible manufacturing and information technologies, increased demand for product/item variety, shorter product life cycles, increased global competition combined with differences in local demand, variety of outsourcing alternatives and turbulent market conditions. In fact, Bask and Juga (2001) argue that competition today is between integrated supply chains rather than individual organizations. An important consequence of such an environment is product/item proliferation. Through item proliferation, it has become a difficult task to forecast demands accurately, which has led to high inventory investment and poor customer service. As Lee (1996) notes, this is a major operational challenge to managers of a manufacturing environment, as it hinders the efficiency of the order fulfillment cycle. Businesses worldwide are striving to achieve effective operational strategies to deal with the growth in product/item variety. Postponement has received attention in tackling this problem.

Postponement is an approach that allows end items to assume their unique identity or functionality as late as possible within their product life cycle. Delaying the timing of crucial processes may mitigate the effects of uncertainties within the production/distribution of the item in the supply chain.

As Kaminsky and Kaya (2008) point out end customers either prefer to find what they are looking for immediately or are willing to receive them in a short amount of time. This creates an opportunity for firms to store intermediate inventory at various facilities in the network. According to the study, a key decision to be made is where to keep safety stock, such that some facilities utilize the advantage of economies of scale by producing to stock while others take advantage of producing to order in order to match good customer service at a price affordable to the customer. The main distinction is thus deciding on integrating a Make-to-Stock (MTS) or Make-To-Order (MTO) strategy. The boundary that differentiates either of the two strategies is termed the 'decoupling point' in literature, which is the trigger point of production activity (Sun *et. al*., 2008). The primary distinction is that a MTS system is based on forecasts, whereas a MTO system is based on actual customer orders. A major problem in supply chains is the limited visibility of real demand. Thus, most organizations are forecast driven rather than demand-driven. The point where market 'pull' meets upstream 'push' is called the decoupling point or order penetration point. The decoupling point dictates the form in which inventory is held, as it separates orders satisfied from planning and those that directly meet customer requirements. In agile supply chains market knowledge is exploited and inventory is carried in a common or generic form until knowledge of actual customer requirements.

Postponement is considered to be a viable strategy if the item forecast is made prior to the decoupling point. Accordingly, before the decoupling point the stocking levels of generic items and not the postponed items need to be kept which creates flexibility in meeting demand requirements (Graman and Magazine, 2006). Delayed differentiation or postponement is considered a hybrid strategy in which a common product platform/item or generic product/item is built to stock. Differentiation is made after demand is realized (Gupta and Benjaafar, 2004).

The authors differentiate manufucturing in two stages:

1) a MTS stage where one or more undifferentiated platforms are produced and stocked

2) a MTO stage where item differentiation takes place in response to specific customer orders.

The make-to-order market is primarily driven by the increased utilization of mass customization and e-commerce practices, which is forcing retailers and manufacturers to shorten planning cycles, manufacturing lead times and expediting distribution (Tyan *et. al*., 2003).

Product/item differentiation is incorporated in order to meet high customer service as well as to expand item variety. Product and process design help reduce the complexity and uncertainty of dealing with a proliferation of items. Garg and Lee (1998) define the process as holding the item in a common (generic) form in the initial stages and by inserting specialized components and/or by performing special processes customizing progressively over the stage(s). The stages at which customization occurs is defined as points of product/item differentiaton. Early postponement and late postponement are possible in delaying differentiation. Early postponement is defined as delaying differentiation at the family differentiation point, while late postponement entails delaying differentiation at the product differentiation point (after the family differentiation point). The study develops necessary conditions for early and late postponement strategies to be optimal. The distinction of early and late postponement in respect to common production strategies mentioned previously can be detailed in Figure 3.1.

Lee and Tang (1997) have investigated the ideal point of differentiation of items in order to improve inventory level and service performance. Rudberg and Wikner (2004) draw attention to the customer order decoupling point (CODP). The decoupling point separates the decisions made under certainty and uncertainty regarding customer demand. The authors use it to classify the value adding activities in terms of the customer demand information. When the CODP is positioned downstream, more value adding activities are carried out under uncertainty. Likewise, as the CODP is positioned further, upstream activities are based on order commitment.

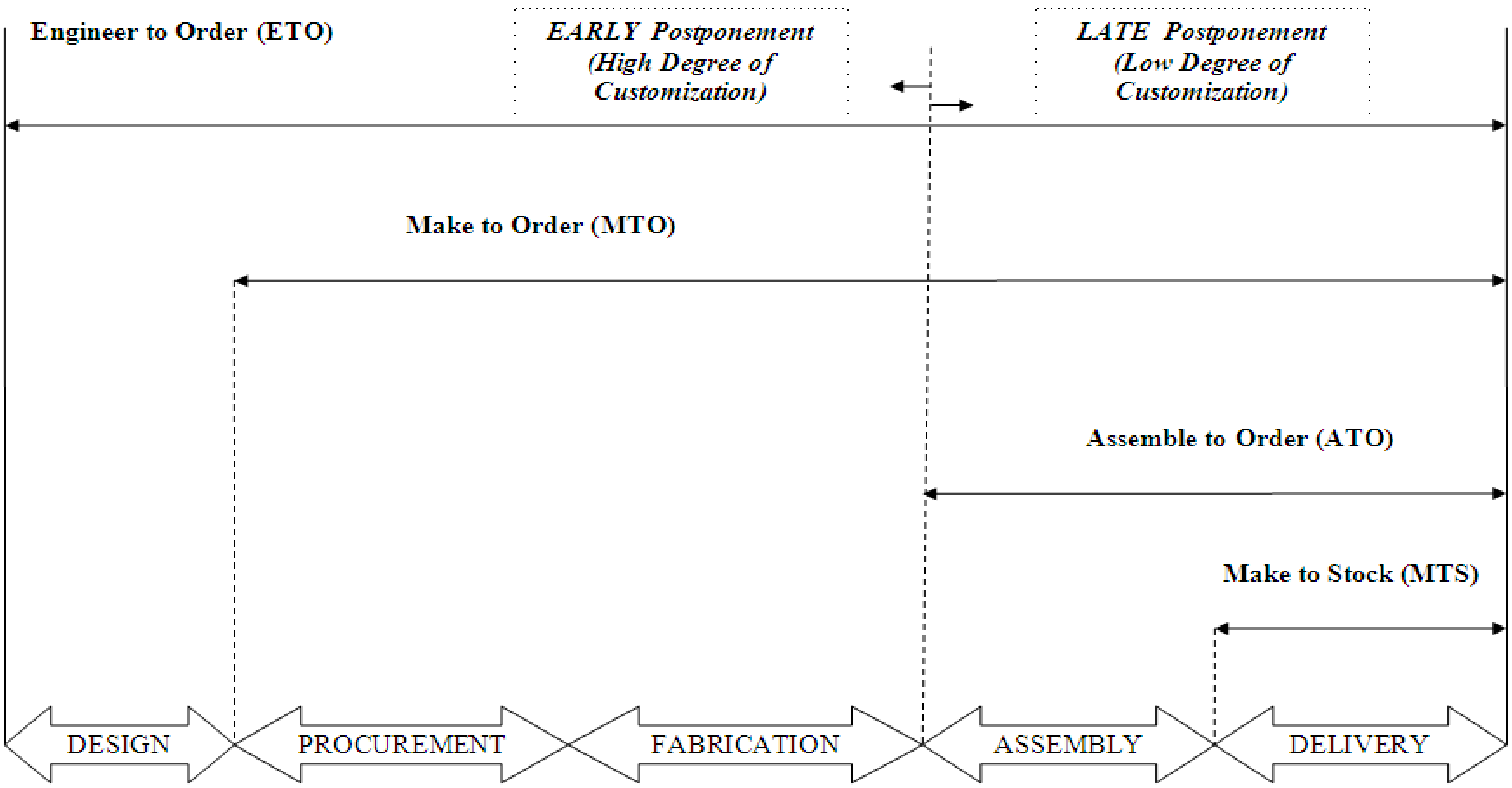

Figure 3.1 Comparison of competitive lead times of various order fullfillment strategies

As Herer *et. al.* (2002) note, the decoupling point separates the supply chain that responds directly to the customer, from the supply chain that uses forward planning and strategic stock to buffer against the variability in the demand of the supply chain. Downstream of the decoupling point, all items are pulled by the customer, likewise upstream to the decoupling point; the supply chain is typically forecast driven. Matthews and Syed (2004) define postponement as a "systematic approach to designing and developing standard and configurable products that can be differentiated quickly and inexpensively once actual customer demand is known".

Matching supply and demand is important in enhancing supply chain effectivity. Many approaches have been entailed to better manage demand including exercising control over prices, inclusion of promotional efforts and enhancing the quality of the services (Gunasekaran and Ngai, 2005). Fisher (1997) distinguishes two main functions of supply chains. The physical function, which involves the transformation, storage and transportation of items within the supply chain and the market mediation function which aims to match demand and supply in today's dynamic environment. Accordingly, uncertainty must be eliminated as much as possible in order to integrate the needs of different parties and carry out the main functions in an effective manner.

Herer *et. al.* (2006) base their work on the classification made by Fisher (1997) with respect to the functions of supply chains. Functional items require lean supply chains, whereas innovative items require an agile supply chain. The concept of leagility is introduced which is the 'capability of concurrently deploying the lean and agile paradigms which hinges on the identification of the decoupling point', a concept enabled by postponement.Vonderembse *et. al.* (2006) extend the main categorization made by Fisher (1997) for innovative and functional items by including a new category of hybrid items. These are a mixture of standard and innovative items.

Mason-Jones and Towill (1998) and Davis (1993) classify uncertainty in the supply chain in four groups:

- **Supply side:** Uncertainty prevalent in supply chains with respect to outside sources that provide resources to the system.
- **Process side:** Uncertainties in production/manufacturing such as uncertainty in yield ratios and cycle times.
- **Control side:** Uncertainties prevalent in the internal decision making process of the supply chain.
- **Demand side:** Uncertainty due to market volatility, as well as varying customer buying behaviors.

Three approaches for demand management discussed in Tang (2006) include shifting demand across time, markets and across items. Postponement is mentioned as an important means to reduce variability in the supply chain. Other demand management initiatives include process sequencing and item substitution respectively. In respect to matching demand with supply, Yang *et. al.* (2007) consider postponement as a way of substituting additional capacity for investment in inventory. Thus, deciding on the amount of postponement activities to be included within a company are critical in overall capacity and asset utilization. Providing excess capacity at the customization point and the control of generic stock is an important consideration in delivery reliability (Skipworth and Harrison, 2006). Postponing is also effective in demand management. Instead of holding large amounts of safety stock, in case demand is higher than expected for any particular SKU, centralizing reduces the number of forecasts made and at the same time increases the accuracy of the forecast by pooling demand uncertainty (Evers, 2001). For example Iyer *et. al.* (2003) utilize demand postponement as a tool to manage demand surges, in situations where demand is likely to exceed short-term capacity. In the implementation a fraction of demands in the regular period are satisfied in a 'postponed' period and a reimbursement is paid to customers who are satisfied in the 'postponed' period. In this manner, stockouts or backorders are preempted, and overall expected costs are reduced.

Mikkola and Larsen (2004) point out those strategies for supply chain integration are empowered by flexibility, agility, cost efficiency and product variety. They define strategies integrating the supply chain as follows:

1) **Mass customization:** Mass customization aims to provide customized items or services in large volumes at competitive prices. Lampel and Mintzberg (1996) identify 5 distinct categories: pure standardization, segmented standardization, customized standardization, tailored customization and pure customization. Gilmore and Pine II (1997) make a classification based on the degree of customer involvement in making the distinction among the choices: collaborative, adaptive, cosmetic and transparent customization. Mass customization makes better use of 'economies of scale', and thus the focus in this strategy is low cost.
2) **Postponement:** Customization of end items is deferred until the latest point in time. The costs of risk and uncertainty are tied to the differentiation of goods.
3) **Modularization:** Modularization is related to both mass customization and postponement. It is an approach that organizes complex items and processes efficiently, by portioning complex tasks into simpler portions. This allows the structure to be managed independently as well as a whole.

A unique framework for evaluating different supply chain structures in the context of modularization and postponement is introduced by Ernst and Kamrad (2000). They link modularization to inbound logistics and postponement to outbound logistics. These concepts are extended such that inbound modularization defines the degree of outsourcing and the usage of subcontractors for making the components. Similarly, outbound postponement captures the extent of customization the supply chain is offering. Taxonomy is defined according to the combined levels of modularization and postponement: rigid, postponed, modularized and flexible respectively. When comparing the strategies it can be stated that modularization is obtained from a product design's point of view, whereas postponement is obtained from a process design perspective.

Studies spanning the use of postponement within the supply chain context are lacking. Sector specific production/service applications are abundant but do not draw attention to common problems or instances that may entice the use of postponement. Yang *et. al.* (2004) have tried to define a framework for this application by trying to fit other concepts dealing with high variability and uncertain demand such as consolidation and rapid response into the postponement context, but it has only been maintained in a categorization.

3.1.1 Types of Postponement

Appelqvist and Gubi (2005) draw attention to the definition of postponement. Some authors define postponement as a differentiating step performed later than usual, while others define it as a means of adding value through variety creation, as all activities are carried out after receiving orders rather than in anticipation of orders. Alderson first identified postponement as a means to reduce marketing cost in 1950. Other names for postponement include end of line configuration, late point differentiation or delayed product differentiation.

Van Hoek (2001) provides an extensive literature review on postponement. The author outlined key research areas and identified issues raised in the study of postponement. These can be summarized as follows:

- The amount and level of postponement application within the supply chain.
- The amount of customization adopted within the supply chain.
- The spatial configuration of the supply chain structure with respect to the postponement activities.
- Operating circumstances in technology, processes and product/item configurations.
- The role of change management.

Van Hoek also provides a general classification for types of postponement:

- **Time postponement** refers to delays in product movement. It entails delaying the foreword movement of goods until customer orders are received
- **Place postponement** utilizes the available storage areas within the supply chain. It stores the items at central locations within the supply chain until the customer orders are received.
- **Form/function postponement** (labelling, packaging, assembly /manufacturing) refers to the delay in the item's final configuration until customer orders are received.

The classification is detailed differently with Bowersox and Closs (1996) where the classification is made according to manufacturing (form) postponement and geographical (logistics) postponement entailing several elements of the above listed types of postponement.

Lee and Tang (1997) derive a classification according to the different postponement strategies implemented within the production and distribution process.

The examples are detailed in the work by Aviv and Federgruen (1998) as follows:

1) **Standardization of components and subassemblies:** Standardization substitutes the initial components with common ones. Thus the complexity of the manufacturing system is reduced.
2) **Modular design:** Describes the degree to which the components of an item can be separated and combined.
3) **Process Restructuring:** The operations are structured so that the commitment to an end item configuration is usually after an order is received from the customer. Common process steps shared by

product/item families are performed first, while steps unique to the item are delayed through postponement of operations (product design) or resequencing of operations (process design).

Based on the state of inventories, four types of postponement strategies can be formulated (Yang *et. al*., 2007). These include:

- **Logistics postponement** creates oppurtunities in the final movement of the items. Transshipment may be considered as logistics postponement, as it delays the point of differentiation which transforms a generic item (an item at any location) into a specific product(an item at a specific location)
- **Production postponement** entails keeping undifferentiated semi-finished items for as long as possible until changes in customer demand are known or finalized. These may include packaging, labelling, assemble to order and make-to-order activities.
- **Purchasing postponement** allows companies to postpone the purchase of incoming components or raw materials until demand is known, eliminating the risk of holding obsolete raw material inventory in stock.
- **Product-development postponement** entails holding no inventory at all as items are engineer to ordered.

The variety of items, parts, suppliers and processes makes businesses more complex and accordingly, complexity brings more uncertainty. Garg and Lee (1998) note that from an operations management point of view, research in the area of item variety is categorized into two classes: non-lead time reduction strategies and lead time reduction strategies. Non-lead time reduction strategies aim to reduce the complexity in the system by reducing the parts and processes in the system. Strategies listed include postponement, part commonality and process sequencing. Lead time reduction strategies aim to reduce the uncertainties by reducing cycle times. Production line structuring and Quick Response systems are examples given in this approach by Yang *et. al.*(2004). In summary, high-value adding activities motivate industries to incorporate demand driven supply chains and utilize different forms of postponement strategy.

3.1.2 Studies on product/item differentiation and its effect on operational flexibility

In postponement applications, which steps and how many steps to postpone are critical topics. Foremost the adoption of postponement is considered to be appropriate for the following conditions as mentioned in Li *et. al.* (2006):

- Innovative products/items
- Items with high monetary density
- High specialization and wide product/item range
- Markets characterized by long delivery time
- Low delivery frequency and high demand uncertainty
- Manufacturing or logistics systems with small economies of scale
- No need for special knowledge

However, there are also barriers to postponement as summarized in the Pratts *et. al.* (2003) study including:

- Lack of understanding of the purpose of postponement
- Inability to evaluate the risks associated with implementation
- Technology limitations to support implementation
- Lack of top-down support, from design through implementation
- Lack of internal and external collaboration
- Lack of information technology that allows companies proper visibility and collaboration

Thonemann and Bradley (2002) argue that high item variety has a negative effect on supply chain performance in terms of replenishment lead time and cost. Moreover the authors argue that companies have to seek out ways to optimize the number of items offered in order to balance the benefits of a larger product/item portfolio for lower supply chain performance. Aviv and Federgruen (2001) also show that holding a non-specific item requires less safety stock compared to holding inventory of specific or customized items. This is a benefit to the use of postponement as it helps inventory reduction and improves overall customer service. In multi-echelon inventory systems this is termed to be similar to the risk pooling effect in supply chains.

In order to reduce the risks associated with item variety, Yang and Schrage (2009) compare four different strategies in literature utilized to achieve demand pooling. The strategies detailed include direct product substitution, transshipment, postponement and use of common components.

Christopher and Towill (2000) and Van Hoek (1998) also mention the importance of holding generic items in inventory. These are:

- If inventory is held in a generic form, there will be ferwer stock-keeping variants and hence less inventory in total.
- Generic inventory creates greater flexibility.
- Forecasting is easier at the generic level than at the level of the finished or customized item.
- Ability to customize items locally may provide an opportunity to create greater variety at lower total costs, which would support 'mass customization' and usage of economies of scale.

The importance of creating operating flexibility to exploit uncertainties is also called 'operational hedging'. Tang and Tomlin (2008) mention the importance of giving multiple facilities or suppliers the flexibility to process items. For example, the authors mention the importance of having flexible manaufacturing processes in dispersed regions or countries, so that a firm utilizes the flexibility of shifting production volume or variety from one plant to another plant in a fast manner.

Van Hoek *et. al.* (2005), analyzed a company which considered both regular production and postponement. In order to better balance the forecasts and demand realizations, they analyzed the efficiency of using a mixture of two technologies: the previous technology producing the generic item ahead of time, while the new technology transforming the item to the desired state, thus determining the optimal inventory levels (produced ahead of time) while minimizing expected cost.

The use of capacitated/staged/partial postponement has also been utilized as creating operational flexibility within the supply chain context. Different sector applications have been seen in the work of Silver and Minner (2005), Zeng, *et. al.* (2006) and Cvsa and Gilbert (2002) respectively.

Kouvelis *et. al.* (2006) differentiate the motive to centralize or decentralize in a supply chain according to the incentive structures within the chain. The authors note that decentralized control policies can be implemented at the functional level however centralization is an approach that maintains better coordinated planning and best optimizes the overall system.

3.1.3 Trends and application areas of postponement

Matthews and Syed (2004) draw attention to postponement by providing the views of 350 supply chain professionals. The study concludes that postponement is a viable and effective supply chain strategy but it has not been effectively used by professionals. This is attributed to the lack of knowledge in this field, deficiencies in technological infrastructure as well as the lack of organizational allignment to undertake this approach. Moreover, increased difficulty in forecasting is a primary driver in adopting a postponement strategy. Some companies combine measures of inventory availability and order cycle time to evaluate service reliability (Graman and Magazine, 2002).

A study conducted by Enslow (2004) reveals that electronics, consumer packaged goods and certain food and beverage manufacturers are prime examples of sectors that benefit from postponement. Various sectors have utilized postponement as an important value adding function for their supply chain. As seen in Table 3.1, automotive supply chains utilize postponement to reduce process lead times and create maximum flexibility within the network. For example, BMW utilizes a COSP (Customer Oriented Sales and Production Process) system which aims to decrease the order cycle time to within 10 working days. Individual customer orders control not only the components supplied and the engine, but also the body and the paint production (Wadhwa *et. al*., 2006). Vonderembse *et. al.* (2006) defines three main items: standard, innovative and hybrid items and their relevance to the design of supply chains. Foremost, the definition of hybrid items resembles the 'postponed' items defined in this work. These items are defined to be a mixture of standard and innovative items.

However it is not very easy to implement postponement all the time. Common dilemmas faced by these sectors include:

- Unstable demand
- Lead times for postponed items should be significantly shorter than the length of the entire supply chain
- Large proliferation of SKU's
- Lack of commonality of components
- Stringent customer service level requirements
- Product lifecycles that span multiple materials buys.

A recent study conducted by Yang *et. al.* (2005) tries to determine the factors that hinder postponement and investigate the potential of postponement in the coming years. The authors compile several aspects that make postponement an integral part of research and practice. These are:

- Increase in items with shorter life cycles
- Increase in item proliferation
- Technological developments continuing at an ever-increasing pace

Table 3.1 Comparison of unique sector and postponement applications

Postponement Sector	Sector characteristics	Type of Postponement	Application Area	Common Performance Measurement	Common Attributes of Items	Authors
Automotive (Industry)	High competition Final product diversity Seasonality	Process Restructuring (Resequencing)	Production Line	Maximal/Cumulative Earliness/Lateness	Body shop-Paint shop-Assembly shop applications	Fournier and Agard, 2007
Automotive (Individual)	Volatility of demand Different product-mix	Logistical	Retainment Platforms Pre-Delivery Inspection Customization to customer wishes	Total response to the needs of customers Timely delivery Absence of error in product and information flows	Not carried in assembly lines, due to excessive delay	Mendonca and Dias, 2007
FMCG and Durable Goods	Wide product range Modularity of products/processes	Logistical and Manufacturing	Appliance, Fashion System and Machine Tools	Inclusion of external players: suppliers and third parties Managing variability of market demands	Compatibility of distribution strategy to service level Amount of modularization.	Battezzati and Magnani, 2000
Batch Process Industries	Value adding by mixing, seperating,forming or chemical reactions'	Component Commonality	Metallurgical industries or food-processing industries	More responsive and minimizing lead time	Productss are very specific to customer demands (variant, size,quality and packaging)	Caux, David, amd Pierreval, 2006
Electrical Motors	High variety Relatively low volumes Reliability and service lead time	Form Postponement	Different motor industries	Delivery reliability Order Lead Time Demand Amplification Capacity Utilizaiton Throughput Efficiency	Demand mix allowed. Variations in customer demand amlified. Product standardization allowed.	Skipworth and Harrison, 2006

- Increased customer involvement and awareness. Likewise, the needs of the customers are also more sophisticated
- Cost and quality are valuable attributes; speed is also becoming a more differentiating factor in success
- Increased interest in mass customization and agility by practioners and researchers
- The abundance of information and communication channels/mediums that introduce new possibilities such as e-commerce
- Awareness to improve the overall supply chain instead of a local aspect of it.

3.2 Inventory management in supply chains with postponement

Lee and Billington (1992) and Ganeshan (1999) site several opportunities that exist in managing supply chain inventories. These include making coordinated decisions between various echelons, incorporating and managing sources of uncertainty and designing proper supply chain performance measures. However, Ganeshan also points out that production and transportation economies need to be incorporated in multi-echelon inventory policy considerations. The ownership and location of physical inventory was best detailed by Wallin *et. al.* (2006) where the authors tries to address the problem of carrying physical inventory and balancing the cost of planning, storing and handling such items. Kouvelis *et. al.* (2006) differentiate the motive to centralize or decentralize in a supply chian according to the incentive structures within the chain. The authors note that decentralized control policies can be implemented at the functional level however centralization is an approach that maintains better coordinated planning and best optimizes the overall system.

Postponed activities are likely to be placed in close proximity to the time and locus of consumption. Accordingly Yang *et. al.* (2007) note that this attribute is reflected in the design of supply chains from item development, sourcing and final distribution of the item. Battezzati and Magnani (2000) draw attention to supply chain characteristics of countries dispersed around the globe. Foremost the structure of the supply chain as mentioned by the authors is determined by geography, culture, legislation and incentives to initiate an entrepreneurial approach.

Er and MacCarthy (2006) draw attention to why companies develop dispersed manufacturing networks. Foremost, dispersed networks maybe associated with long lead-times and greater delivery uncertainty due to geographical distance and political concerns.

Accordingly they analyze item variety in both a local and international context drawing attention to the demand uncertainty and supply lead-time uncertainty faced in both contexts. Among the distinctive differences, Lowson (2001) indicates that in accomodating volume and mix changes domestic suppliers are more flexible and responsive than international suppliers. The authors gather several reasons on why companies prefer to work in non-local settings including reduction of costs, accession to new markets as well as seeking strategic assets, such as labor and/or technology.

There has been a variety of literature published on multistage inventory systems. In accordance with our study, those entailing arborescent, two-echelon structures in a periodic review environment are detailed. Attention has been drawn to allocation policies that supplement our work. Postponement strategies within the echelon structure have also been exemplified. Moreover, the concept of risk pooling as well as transshipments have also been detailed in accordance with our work.

In multi-level inventory systems centralization or 'risk pooling' at the central production facility is assumed to improve the cost effectiveness of the system. This was illustrated by Eppen in 1979 and also emphasized in the work by Schwarz 1989. In Eppen's scenario customers were indifferent between being served by a central site or by local (decentraized) sites.

The study showed that the expected cost of the decentralized system grew linearly with N, the number of retailers, while the expected cost of the centralized system grew with $\sqrt{N}$. This is termed to be the portfolio motive or risk pooling incentive for centralizing inventories.

Cohen and Lee (1988) formulate a two echelon distribution system with N retailers where contrary to previous work by Federgruen and Zipkin (1984), the central production facility is allowed to hold stock during the period. A pure distribution system, with no transshipments and stock returns are analyzed. If at the beginning of the period (referred to as the 'runout period' by the author) the central production facility stock is insufficient, then all remaining stock at the central production facility is withdrawn and distributed to maximize the minimum retailer inventory. Using a ship-up-to-S allocation policy, the author showed the benefits of centralizing a portion of the total system stock, for the case of identical retailers. Thus ensuring a more balanced distribution of stock towards the end of the cycle and therefore better performance overall.

Schwarz (1989) examines two different multi-location replenishment inventory models in a periodic setting to ensure the value of centralized warehouse risk-pooling. This is attributed to the timing of the system order. The first system allocates the system order to its retailers at the beginning of its supplier lead time, while the second system allocates the system order at the end of its supplier lead time. The author determines the break-even point between the two systems with regard to the additional lead time.

Tagaras (1999) and Heijden (2000) also analyze (R, S) systems in a one warehouse, N retailer setting. Tagaras works with installation inventories and tries to solve the order-up-to quantities by calculating a mathematical model including holding, shortage and transhipment costs. Heijden works under an echelon stock policy with the objective of achieving target fill rates and minimizing total holding costs of the network analyzed, which is also considered under a two-echelon setting.

Sobel and Zhang (2001) analyze a periodic review inventory system in which the authors account for both deterministic and stochastic demand. The deterministic demand is required to be satisfied as it arises, and the stochastic source is allowed to be backlogged. The work draws attention to the 'Issuing Policy' which protects high priority customers through high penalty costs and delaying the fullfillment of demand of low priority customers.

Monthatipkul and Yenradee (2008) extend the inventory/distribution problem in a single warehouse and multi-retailer setting utilizing appropriate safety stock factors at the warehouse and retailers. The system does not allow transshipment but is an important contributor in defining total system costs and echelon (R, s, S) stock policies respectively.

Managing the quantity and place of strategic stock placement has been detailed extensively by the work of Graves and Willems (2000) and Kukreja *et. al.* (2001). Both work under a multi-echelon setting but Kukretja *et. al.* (2001) work under a continuous review policy. The effect of lead times and safety stock placement under various processing stages are detailed and is an important contributor to understanding the shifting of inventory locations under a multi-stage setting.

Various allocation (rationing) policies are abundant in literature. The most prevalent techniques are fair share rationing, priority rationing, consistent appropriate share and balanced stock rationing respectively. The various allocation policies are briefly introduced below:

Fair share rationing: Rations the available material so as to maintain all end stock points inventory at a balanced position; that is all having the same stockout probability. Verrijdt and Kok (1996) note that most applications in literature tend to differentiate the service levels at each of the lower echelon end-points, which would imply that the equal stockout probability (fair share rationing) is not valid and is a myopic strategy.

Priority rationing: Produces a list of the end-stock points and rations the available material so as to satisfy them in the sequence they were listed. Under priority rationing, all rationing decisions are effectively determined by the orders released by individual end-stock points. However, this strategy is not preffered due to the risks of the bullwhip effect.

Consistent Appropriate Share: Inventory is allocated to the local stockpoints based on safety stock ratios.

Balanced Stock: Inventory is allocated according to a predetermined ratio of the total central production facility inventory.

In order to avoid unnecessary delays that increase flow times within the system, remedies to working with critical items are mentioned by several authors (Er and MacCarthy, 2006; Lee, 2002) including increasing safety stock and applying risk pooling techniques for critical materials, arranging service level agreements between manufacturers and suppliers, placing buffers in uncertain parts of the supply chain and incorporating penalty costs for late deliveries.

Cachon (2001) mentions that when firms implement re-order point policies, a retailer's average total cost does not have any impact on the other retailers and is determined according to its own re-order point as well as its main source provider (in our case it is the central production facility). Tagaras and Vlachos (2002) point out that the economic benefits of pooling are larger when the shortage cost is higher, the transshipment cost is lower and the regular replenishment lead time is longer.

Yang and Schrage (2009) summarize different methods of demand pooling found in literature including direct item substitution, transshipment, postponement and the use of common components. The authors draw attention to the risks involved in such systems using experimental analysis. Pooling through transshipment is detailed extensively by the work of Dong and Rudi (2004). The concept of full pooling, partial pooling and not pooling are mentioned according to the cost structure evident in the transshipment policy. Morever, allowing the substitution of items are also detailed in the analysis.

3.3 Transshipments

Redistribution of items (generic and/or customized) helps to reduce the possibility of inventory imbalance among the various retailers. Inventory levels can become unbalanced due to random variations in demand. Van der Heijden *et. al.* (1999) define imbalance as the 'deviation of the inventory position of stocking locations from the average inventory position'. Transshipment is an effective mean to redistribute inventory located at different places at varying times, particularly between stocking points within the same echelon. Accordingly, the performance of the system can be improved in terms of service and cost when retailers jointly collaborate in cases of shortages by means of lateral inventory transshipment. Retailers that share their inventory through lateral transshipments are said to form a 'pooling group' (Tagaras and Vlacious, 2002). Transshipment categorization in literature is based according to when demand is realized.

Transshipment in anticipation of a future requirement is termed preventive transshipment and it permits transshipments and redistribuiton of stock between locations during the order cycle before demand is observed. Preventive transshipments allow transshipments before demand is realized, whereas emergency transshipments allow transshipments after demand is realized but not satisfied as defined by Herer *et. al.*(2002). Preventive transshipment has been utilized as a balancing mechanasim in periodic review models to reduce systemwide costs (Olsson, 2009). Emergency replenishment can be carried out if the expected arrival time of the pipeline order is greater than the emergency transshipment time. The quantity shipped will depend on the pooling policy in force and its control parameters. Another distinction by Banerjee *et. al.* (2003) categorizes emergency ad-hoc transshipments as short term with a local focus and preventive transshipments based on inventory balancing and equalization-based lateral shipments, with longer term more global consideration. Allowing transshipments, as the demand is being realized has also been studied in literature, but has not been widely used.

An example to this concept is the use of rolling warehouses (a variant of logistics postponement) where the vehicles's schedules and routes are re-planned (towards a better utilization of the vehicle), while on the road (Yang, 2005). Transshipment lead time LT_{ij} is assumed very small due to the proximity of the retailers, but it is not neglected as done by most studies in literature. Thus, the general approach aims to balance retailer inventories for varying items and creating better performance with regard to the backorder of items caused in the system. As in postponement, transshipments transform the generic item (item at any location) into a specific item (an item at a specific location) in a relatively short time.

A good transshipment or redistribution policy should not deteriorate total group performance (Tagaras and Vlacious, 2002). The work of Johnsson and Silver (1987) is important in transshipment literature as it gives an idea on the ideal timing of transshipment. The authors show that for demand with a moderate coefficient of variation (i.e less than 0.5), backorders are unlikely to occur until the last period before replenishment. Thus, in a system with an H review period, the redistribution of the stock is allowed at the end of the (H-1) st period.

Foremost, the type of item being transshipped has also been a consideration within the study. For example, some researchers have analyzed lateral transshipments with respect to repairable and recoverable items, while others have focused exclusively on consumable items.

In previous studies on transshipment several common features can be observed, as mentioned and summarized in Evers (1997) study which include the following:

- Transshipment times are assumed instantaneous
- Customers (retailers) are allowed multiple shipments
- If demand cannot be filled even after transshipments this results in

stockout and demand is lost.

3.3.1 Description of the transshipment policies

a) Preventive (Proactive) transshipment

Johnson and Silver (1987) draw attention to the timing of transshipments in literature. Especially as a proactive approach, to prevent inventory shortages before they occur, the authors make a study on the best timing for the inventory. Tagaras and Cohen (1992) point out that the ideal transshipment/ pooling policy is based on information about the timing and magnitude of all outstanding orders at both locations. As Herer *et. al.* (2002) points out, transshipments reduce the overall lead time to reach the customer by eliminating wasted time by allocating from the central production facility which is an important benefit in volatile markets. In our study we have not restricted the timing of proactive transshipments but as a general rule determined up to what point this initiation maybe made. In example, the retailers have a review period R_i, which determines the time between successive reciepts of orders from the central production facility. If $t=0$, then $t+R_i$ is the last time unit in which regular order is received from the central production facility. Accordingly, the transshipment per review period should be at the end of time unit t such $t<R_i-L_i$ in order to prevent serious stockout.

b) Reactive transshipment

Within the time of replenishment in any case of shortage, transshipments are initiated among the retailers. Emergency transshipments can be made among the retailers according to several policies. Among the policies faced predominantly within this reactive approach include priority shipments and random allocation rules. Priority shipments rely mainly on giving priority to certain orders with respect to the subject (i.e from a certain retailer i) or with respect to time (i.e which order was initiated first for any of the items among the retailers).

Random allocation does not define strict rules in allocation. It primarily bases the decisions according to product availability in any of the retailers.The problem that has been defined in this work will rely on random allocation. Thus, in order to initiate reactive (emergency) transshipment, basicly the condition of $I_i^k(t) \leq s_i^k(t)$ $\forall i : 1,2,...,N$ and $\forall k : 0,1,...,M$ holds which would imply that there is a shortage at location i of item k at time t or when the item demanded is in a backorder state B_i^k(t).

Axater (1990) extends the work for repariable items in literature, with a one-for-one replenishment policy in a two echelon setting. The paper is unique to introduce pooling groups within bases where transshipment is allowed. Also, demand rates at the bases are structured so that they are dependent on the inventory situation. The work proved to be effective in non-identical bases as well, different from the previous work in this field.

Betrand and Bookbinder (1998) uniquely extend the transshipment problem by assuming non-identical costs at the stock keeping locations with stochastic inventory for consumable items. The authors mention that it is an advantage to use transshipment (redistribution as they term it) when replenishment occurs periodically because the stochastic demand may cause some locations to face shortages while others to have excess.

The authors analytically conclude that redistribution reduces the variance of the net inventory prior to a new order. Furthermore, the net benefit on redistribution depends on the magnitude of holding, shortage and transshipment costs respectively.

Herer *et. al.* (2006) primarily deal with the transshipment problem and they extend transhipment to a multiple retailer setting utilizing different cost structures and demand parameters. The problem is formulated as a network flow problem, which is critical in system assessment and analysis.

Transshipment and/or logistics postponement necessitates the use of quick and reliable transport modes. Accordingly, faster transport may assist in postponing production. Moreover, e-business activities are also enforcing more frequent and smaller sized shipments over long distances which are also an important consideration in utilizing transshipment techniques (Yang et. al. 2003).

3.4 Importance of Risk Pooling

In order to avoid unnecessary delays that increase flow times within the system, remedies to working with critical items are mentioned by several authors (Er and MacCarthy, 2006; Lee, 2002) including increasing safety stock and applying risk pooling techniques for critical materials, arranging service level agreements between manufacturers and suppliers, placing buffers in uncertain parts of the supply chain and incorporating penalty costs for late deliveries. The majority of the literature uses order-up-to-level inventory models, in which the order size, number of pending orders and number of end products are not affected within this selection (Gupta and Benjaafar, 2004). Cachon (2001) mentions that when firms implement re-order point policies, a retailer's average cost does not have any impact on the other retailers and is determined according to its own re-order point as well as its main source provider (in our case it is the central production facility). Tagaras and Vlachos (2002) point out that the economic benefits of pooling are larger when the shortage cost is higher, the transshipment cost is lower and the regular replenishment lead time is longer.

Yang and Schrage (2009) summarize inventory management policies seen in literature that have investigated product/item substitution. Various underlying assumptions include substitution structures (full-partial-one-way-two-way), cost (symmetric-asymmetric) and demand distributions. However, substitutions are often done with an item of higher value in order to satisfy the customer. However, in this instance the customer is fulfilled but an extra cost on the supplier is inflicted. Pooling through transshipment is detailed extensively by the work of Dong and Rudi (2004). The concept of full pooling, partial pooling and not pooling are mentioned according to the cost structure evident in the transshipment policy. Morever, allowing the substitution of items are also detailed in the analysis.

3.5 Effect of modelling assumptions and performance measurement

Multilevel echelon problems entailing two or more levels receive significant attention in literature as referenced and analyzed in the work of Van der Heijden *et. al.* (1997), Lee and Wu (2006), Tyagi *et. al.* (2004) and Gürbüz *et. al.* (2007). Most are at a two-level dimension because supply chain structures exceeding two levels entail restricted assumptions such as the use of identical retailers, Normal or Poisson demand distributions, fixed or zero lead times which are summarized in the work of Venkateswaran and Son (2004) and Hwarng *et. al.* (2005).

Relaying true information is important and vital in the flow of operations. Rabinovich and Evers (2003) point out that to utilize demand data correctly, it is necessary that consolidated stock keeping locations need timely demand data from the marketplace. Likewise, those locations providing emergency transshipments should also be in interaction to properly follow up orders and determine where to satisfy demand information from.

Rao (2003) provides an extensive study on the properties of periodic review (R, T) Inventory control policies. It focuses on stationary stochastic demand, different from general literature using deterministic demand. The author also computes inventory cost continuously, different from traditional formulas that approximate inventory costs at the end of each replenishment cycle.

Lau *et. al.* (2008) investigates the choice of inventory policy to the effects of information sharing and early order commitment. Order commitment, is another unique approach to handle variation in demand instead of utilizing a postponement strategy. The authors show through simulation that information sharing is beneficial for the supplier more than the retailer, however early order commitment is effective in reducing total cost. Peidro *et. al.* (2008) also mentions the importance of simulation in supply chain modelling.

Performance measurement is defined as ‘the process of quantifying the effectiveness and efficiency of action’. Lambert and Pohlen (2001) note that metrics are needed to remain competitive and to differentiate product and service offerings of the distinctive company. As mentioned in Beamon (1999) and Persson and Olhager (2002) two types of performance measurements dominate in supply chain literature including quantitative and qualitative measures, as well as cost and customer responsiveness measures. Cost measures include inventory and operating costs, whereas responsiveness measures entail lead-time, stock-out probability and fill rate measures. However, Beamon (1999) also advocates ‘integrated’ measures and supports the use of ‘mix’ of measures representing resources, output and flexibility of the system. Resource measures indicate the level of efficiency in the system. Output measures aim at measuring and attaining high level of customer service and lastly flexibility measures reflect the ability of firms to respond to changing environments.

CHAPTER 4

EVALUATION OF THE SYSTEMS

Customer expectations have increased, thus customers demand more item variety with lower costs and faster response times. Supply chain strategies should incorporate customer expectations and be able to offer a vast number of items with different characteristics in a competitive manner. Inventory management policies are an important contributor to system performance in supply chain activities working under different policies and environmental considerations.

4.1 Policies utilized in the systems

The common policies included in the systems and the calculations of relevant input parameters are mentioned in the respective sections. Explanations regarding system implementation, notation and assumptions are also detailed.

4.2 Parameters and notation

Indices:

i: Facility index, $i= 1,2,\ldots,N$. There are N retailers in the system. As a production facility, the central production facility is included as $i=0$.

k: Item index, $k=0,1,2,\ldots,M$. There are $M+1$ different product (item) types including the generic item denoted by k=0.

Parameters:

L_S	Supplier lead time; lead time for raw material procurement from the supplier to the central production facility.
τ_0	Central production facility generic lead time; lead time to convert raw material to generic item at the central production facility.
τ_k	Customization lead time; lead time to convert generic item to customized item k.
L_w	Central production facility production/manufacturing lead time; $L_w = \tau_0 + \tau_k$ with customization and $L_w = \tau_0$ without customization.
L_0	Replenishment lead time; $L_0 = L_s + L_w$.
L_i	Distribution/Transportation lead time; lead time to transport the items from the central production facility to retailer i, or the average delay time in filling a retailer's order.
LT_{ij}	Transshipment lead time; time to carry an item from retailer i to retailer j.
D_0	Delay at the central production facility/retailer in converting generic items into customized items because it was not available at the point of request.
R_0	Periodic review period for the central production facility.
R_i	Periodic review period for retailer i.
$D_{i,Li}$	Demand at retailer i during a distribution lead time L_i; a random variable with mean $\xi_i = \mu_i L_i$ and standard deviation $\omega_i = \sigma_i \sqrt{L_i}$.
$D_{i,Li+R}$	Demand at retailer i during the distribution lead time plus review period.
$L_i + R_i$	A random variable with mean $\upsilon_i = \mu_i (L_i + R_i)$ and standard deviation $\varphi_i = \sigma_i \sqrt{L_i + R_i}$.
$d_i^k(t)$	Retailer i demand for item k at time t; a random variable with mean μ_i and standard deviation σ_i .

σ_i^2 — The variance of demand at retailer i is the sum of the variances of the individual items; $\sigma_i^2 = \sum_{k=0}^{M} \sigma_{ik}{}^2$.

μ_i — The mean of demand at retailer i is the sum of the mean of the individual items for that particular retailer i; $\mu_i = \sum_{k=0}^{M} \mu_{ik}$.

$D_i^k (t_1, t_2)$ — Demand at retailer i for item k in the period $[t_1, t_2]$; $D_i^k (t_1, t_2) = \sum_{r=t_1}^{t_2} d_i^k (r)$.

$D_i(t_1,t_2)$ — Retailer i demand at time $[t_1, t_2]$; $D_i(t_1,t_2) = \sum_{k=0}^{M} D_i^k(t_1,t_2)$.

$D_0^k (t_1, t_2)$ — Systemwide total demand faced at the central production facility in period $[t_1, t_2]$ for item k; $D_0^k (t_1, t_2) = \sum_{i=1}^{N} \sum_{k=0}^{M} D_i^k (t_1, t_2)$.

$D_0(t_1,t_2)$ — Systemwide total demand in the period $[t_1,t_2]$; $D_0(t_1,t_2) = \sum_{i=1}^{N} D_i(t_1,t_2)$.

$D_i(t)$ — Net demand at retailer i at time t. $D_i(t) = \sum_{k=0}^{M} D_i^k(t)$.

q_i — Allocation fraction for retailer i.

f_i — Allocation rule for retailer i.

Cost Parameters:

t_i — Transportation cost per unit item transported from central production facility to retailer i.

h_i^k — Holding cost incurred at central production facility/retailer i per unit item k held per period, where i=0 is the central production facility.

p_i^k — Penalty (shortage) cost per unit held per period at retailer i for item k.

c_{ij} — Transshipment cost per unit item transshipped from retailer i to j.

f_i^k — Finalization or customization cost per unit item k at location i.

A_i	Fixed ordering cost for the retailers and the central production facility.
s_k	Salvage value per unit of item k.
r_k	Revenue per unit of item k.

Auxiliary Variables:

$OH_i^k(t)$	On- hand inventory at retailer i and central production facility for item k at time t.
$B_i^k(t)$	Outstanding backorders at time t at retailer i for item k.
$O_i^k(t)$	On-order inventory at retailer i for item k at time t.
$U_i^k(t)$	Net inventory of retailer i for item k before demand realization at time t; $U_i^k(t) = OH_i^k(t) - B_i^k$.
$U_i(t)$	Net inventory of retailer i before demand realization at time t; $U_i(t) = \sum_{K=0}^{M} U_i^k(t)$.
$I_i^k(t)$	Net inventory at retailer i for item k after demand realization at time t; $I_i^k(t) = U_i^k(t) - d_i^k(t)$.
$I_i(t)$	Net inventory of retailer i after demand realization at time t; $I_i(t) = U_i(t) - D_i(t)$.
$J_i^k(t)$	Inventory position of retailer i for item k after ordering at time t; $J_i^k(t) = OH_i^k(t) - B_i^k(t) + O_i^k(t)$.
$J_i(t)$	Inventory position at retailer i after ordering at time t; $J_i(t) = \sum_{k=0}^{M} J_i^k(t)$.
$J_R(t)$	Ecehelon inventory position of the retailers; $\sum_{i=1}^{N} J_i(t)$.
$U_0^k(t)$	Net inventory at the central production facility of item k before demand realization at time t.
$U_0(t)$	Net inventory of central production facility before demand realization at time t.

$IG(t)$	Net inventory of generic items at the central production facility at the end of time t.
$XR(t)$	Quantity of raw material completed at the central production facility and added to generic inventory at the start of time t.
$F_k(t)$	Net inventory of customized (finished) item k at the end of time t at the central production facility.
$Y_k(t)$	Amount of generic items converted to customized item k.
$Y(t)$	Amount of items that are customized at the central production facility; $Y(t) = \sum_{k=1}^{M} Y_k(t)$.
$Q_i^k(t)$	Size of replenishement order for generic or customized items at retailer k.
$Q(t)$	Amount of replenishment orders for all the retailers at time t; $Q(t) = \sum_{k=0}^{M}\sum_{i=1}^{N} Q_i^k(t)$.
β_i	Fill rate at retailer i
S_i^k	Order-up-to level of item k at retailer i. There are $M+1$ products demanded by the customers. It is assumed that one unit of generic item produces a unit of customized item respectively.
S_i	Echelon Order-up-to level at retailer i ; $\sum_{k=0}^{k=M} S_i^k$.
S_R	Total order up-to-level of all retailers ; $\sum_{i=1}^{N} S_i$.
S_0	Echelon order-up-to-level at the central production facility.
SS_i^k	Safety Stock level of item k at retailer i.
SS_0	Safety Stock level at the central production facility.
Δ	Imbalance between central production facility and retailer requests; S_0-S_R.
T_{it}	Quantity sent from the central production facility to retailer i at the beginning of time t.
$B_i(t)$	Binary variable representing whether an order is placed by retailer or central production facility i at period t.

$IP_i^k(t)$	Inventory position of item k at retailer i after demand occurs, but before transshipment and reordering occurs.
$IN_i^k(t)$	Net inventory of item k at retailer i after demand occurs, but before transshipment.
$IT_i^k(t)$	Inventory level of item k at retailer i, immediately after transshipments and demand satisfaction.
X_{ijt}^k	Amount of item k transshipped from retailer i to j at time t.

4.3 Inventory Policy

The system analyzed is a production-inventory-distribution system with two echelons and multiple end items. Foremost, the total number of items demanded over a fixed time period is also a random variable and its probability distribution is assumed to be the same for each period of length t, with mean and variance parameters D(μ_{ik}, σ_{ik}^2) and normally distributed. Flexibility is reflected in the system with the order quantity, which is a function of the magnitude of demand during the replenishment cycle. If the retailers are given the capabilities to customize, customization is carried out after the realization of demand. Otherwise they are customized at the central production facility. Prior to the demand realization the generic and/or customized items are to be distributed among the retailers. If there are enough items at the central production facility to satisfy all the retailers, then the items can be accordingly distributed to the respective retailers.

However, if the amount of items at the central production facility falls short of the total demand at the retailers, then the generic items have to be rationed among the retailers. There are *M* different possible item(product) alternatives or customized items offered to the customer. Accordinlgy, if the production facility and/or retailer is allowed to hold a generic item, there are then *M+1* inventory items at the retailers. The timing of a particular demand is usually not predetermined and is a function of the customer; accordingly the interarrival times of the customers are assumed to follow an exponential distribution. The quantity demanded and the demand arrival times contribute to the stochastic nature of the systems. The amount to be produced within the total supply chain is thus a function of the demand parameters at the retailers which will be critical in determining the order-up-to-levels at retailer i for the items. The order-up-to level for the central production facility is a function of the aggregate demands faced by the retailers for various items.

Inventory is reviewed periodically both in the central production facility and at the retailers. The central production facility utilizes an (R_0, S_0) order-up to strategy, where every review instant (R_0 time units) enough raw material is ordered from the supplier to raise the inventory position of the central production facility to S_0 which is the overall generic item requirement of the retailers.

The retailers utilize an $\left(R_i, s_i^k, S_i^k\right)$ inventory policy. Every R_i review period instance, the inventory position of the retailers are checked. At the review period R_i, if the inventory positions of item k at retailer i is at or below the re-order point s_i^k, an order is initiated to the central production facility to raise the inventory position to S_i^k. If the inventory position for all of the items is above their re-order level s_i^k, no order is placed until the next review interval R_i. More formally, if our observed inventory level is $I_i^k(j)$ after demand realization at the j^th review point, the order of size $Q_i^k(j)$ is placed as follows:

$$Q_i^k(j) = \left\{ \begin{array}{c} 0, \ I_i^k(j) > s_i^k \\ S_i^k - I_i^k(j), \ I_i^k(j) \le s_i^k \end{array} \right\} \quad \textbf{(1)}$$

The review mechanisms at the retailers include re-order levels, as they may hold value-added items in close proximity to the customers that require quick service. Instead of ordering at every review instance, the re-order level brings a control mechanism for the operations that are carried out at the retailer. In order not to disrupt supply chain dynamics, the re-order level is kept high, where the retailers consistently order at every review period.

4.3.1 Order-up-to-levels

For a periodic review system, the safety stock should be positioned such that it creates bounds for the inventory held at a certain stocking point (central production facility/retailer). Thus, the safety stock should provide protection for the retailers for the replenishment interval plus the transportation lead time. The retailers face the demand of items; accordingly the order-up-to-level S_i^k for each of the retailer i for item k can be represented in the following form over a time period of τ to be: $S_i^k(\tau) = \tau\mu_{ik} + k_i\sigma_{ik}\sqrt{\tau}$. Thus for retailer i facing demand for item k, the order-up-to levels S_i^k are set as follows:

$$S_i^k = \mu_{ik}(R_i + L_i) + k_i\sigma_{ik}\sqrt{R_i + L_i} \quad \textbf{(2)}$$

for a single item requirement k at retailer i. The k_0 and k_i value is a constant reflecting the percentage of time that the safety stock covers the demand variation for the central production facility as well as the retailers. Accordingly it is a safety factor specifying the amount of inventory, management is willing to tolerate in its calculations. Specifically a 95% service level corresponds to k=1.65, assuming a normally distributed demand (Graves and Willems, 2000).This structure is still valid for systems with a reorder level s_i^k respectively.

The order-up-to level should cover the review períod as well as the dístribution lead time to reach the premises of the system. The echelon oder-up-to-level of a retailer is thus:

$$S_i = \sum_{k=0}^{k=M} S_i^k \quad \textbf{(3)}$$

However, the demand faced by the central production facility is to be approximated as normally distributed with the sum of demand rate parameters for different retailers. Thus the mean and variances are taken at an aggregate level. The central production facility orders every R_0 periods and not in between, protection is required only for R_0 for the customized items, where $L_s + L_w = 0$. For other inventory items held at the central production facility, protection is required for the supplier lead time, as well as the production lead time. For example, for the generic item protection is required for $R_0 + L_w$, whereas for the raw material protection is required for the supplier lead time and thus $R_0 + L_s + L_w$ respectively. Thus, the order-up-to-level for the central production facility becomes for the different inventory items:

$$S_0 = (\mu_1 + \mu_2 + \mu_3 + ... + \mu_N)(R_0 + L_s + L_w) + k_0\sqrt{\sigma_1^2 R_1 + \sigma_2^2 R_2 + ... + \sigma_N^2 R_N} \quad \textbf{(4)}$$

which is also mentioned in the work of Graves and Willems (2000).

4.3.2 Safety Stock levels

To protect against demand uncertainty, safety stock is allowed at the central production facility as well as at the retailers. The safety stock level at each retailer i for each distintictive item k is defined to be $SS_i^k = k_i \sigma_{ik}$ if distribution and production lead times are assumed to be negligible. However, in periodic review systems, this can hinder system performance by not covering the true lead time demand. Thus, for each retailer the safety stock level is approximated to be:

$$SS_i^k = k_i \sigma_{ik} \sqrt{R_i + L_i} \quad \textbf{(5)}$$

According to the order-up-to definitions, the average safety stock at the central production facility based on total customized item requirement thus becomes:

$$SS_0 = k_0\sqrt{\sigma_1^2 R_1 + \sigma_2^2 R_2 + \sigma_3^2 R_3 + ... + \sigma_N^2 R_N} \quad \textbf{(6)}$$

4.3.3 Re-order level

If the current re-order level of any item k for retailer i is reached at the review time, then an order size as a function of the order-up-to level at retailer i for specific item k is requested. The re-order level is a function of the expected demand and the safety stock level associated with retailer i and item k. Determination of the re-order level is a function of management policy. The re-order quantity regulates unnecessary ordering and creates a distinction among the types of inventory held at the retailers. For example, if an item is higly requested by the retailers, the re-order level would be higher than any other item that is demanded. In the system implementations, the re-order level has been held quite low with respect to the demand of items, thus minimizing the effects with respect to the wrong choice of re-order level.

4.3.4 Ordering policy

The ordering policy both at the retailers as well as the central production facility is an important concern in handling the demand requests. There are three main alternative policies for the central production facility and the retailers:

a) $R_0=R_i$; the central production facility and the retailers order at the same time. This is a viable alternative if the retailers are replenished instantaneously. However, if there are customized items avaialable at the central production facility, there is a distribution lead time, L_i, from the production facility to the retailers that needs to be covered througout the demand instances at the central production facility.
b) $R_0<R_i$; the central production facility orders more frequently than the retailers. However, this is not a feasible policy, since the supplier providing the raw materials to the central production facility is uncapacitated and there is no risk of in-transit inventory loss.

c) $R_0 > R_i$; the retailers order more often than the central production facility.

Among the retailers there are also different review policies that may be undertaken. Foremost, if in the system there are two retailers: Retailer 1 and Retailer 2, the review instances may accordingly be defined as follows:

a) $R_1=R_2$; the retailers are assumed to order at identical review times for their orders. This is a common assumption as the central production facility may simultaneously deliver the requested quantities to neighbouring locations. However, this assumption implies that all retailers are similarly low in inventory near the end of their common review cycle (Tagaras and Vlachos, 2002).

b) $R_1 \neq R_2$; the retailers have different ordering review periods. This is an important consideration in evaluating pooling groups to mitigate the risk of inventory backorders in the respective retailers.

However, the selection of either of these two policies is expected to be a function of the number of retailers and demand variation faced at the retailers.

4.3.5 Rationing policy

An appropriate rationing or allocation rule helps to correct the deviations of the actual demand from the expected demand during the period. In other words, system imbalance is avoided by having aggregate excess stock at the local stockpoints. Thus, less inventory is required to attain a target customer service level. The inventory positions at the retailers and at the central production facility are critical in the assessment of a rationing policy. The retailer inventory position includes on hand inventory plus inventory in-transit from the central production facility to the respective retailer minus any possible backorders. The central production facility inventory position, on the other hand, is the sum of on-hand inventory and inventory in-transit from the raw material supplier plus all downstream inventories including pipeline inventories. If all retailer orders can not be fulfilled by the on-hand inventory at the central production facility, the available inventory will be rationed such that it maximizes the minimum inventory position through the balanced stock rationing rule as defined in Fransoo *et. al.* (2003) and Lagodimos *et. al.* (2008) based on the retailer average demand and variance as follows:

$$f_i = \frac{\mu_i^2}{2\sum_{j=1}^{N}\mu_j^2} + \frac{\sigma_i^2}{2\sum_{j=1}^{N}\sigma_j^2} \quad \text{and} \quad \sum_{j=1}^{N} f_i = 1 \qquad \textbf{(7)}$$

The balanced stock inventory allocation procedure ships a predetermined ratio of the total central production facility inventory in case retailer demands exceed available inventory at the central stocking position. The rationing is conducted according to the total retailer demands.

4.4 Stock Policy of the investigated systems

Centralized demand information is utilized by echelon-stock policies while installation stock polices require only local information. Focusing on echelon inventory and disregarding installation (retailer) inventory information may result in backorders at some of the retailers, if all customer demand comes from a single retailer. Accordingly, when the central production facility receives shipment from the supplier and accordingly converts the item to the desired state, it is important to distinguish if inventory allocation of orders will be based on net inventory or inventory position of the retailers. Delaying the allocation decision would benefit the retailers by lowering inventory related costs. Accordingly, utilizing postponement in such instances is a viable alternative as mentioned by Gürbüz *et. al.* (2007). The decisions in the systems are carried out considering backorder and on-order inventory, and the net inventory available at the premises of the central production facility and /or retailers.

4.5 Modelling assumptions

The assumptions in our study include the following:

1) Customer demand only occurs at the lower echelon at the retailers.
2) The demand for any item per period is normally distributed and stationary in time and realized at the end of each period.
3) The demand for any item is both independent across local stockpoints (retailers) and across periods in time.
4) Demand arrivals are stochastic and are assumed to follow an exponential distribution.
5) Demand at any retailer i is fully backordered based on a FCFS principle. There is no lost sale in the systems.
6) At any time t, $I_i^k(t)$ and $B_i^k(t)$ should not both be positive. If $I_i^k(t)$>0 then $B_i^k(t)$=0, likewise if $B_i^k(t)$>0 then $I_i^k(t)$=0.
7) The central production facility orders from an external supplier which is assumed to have an infinite capacity, thus orders of the central production facility are fully satisfied. However, the retailers may not always be fully satisfied and the central production facility may need to ration the available items to the retailers.
8) There are no capacity constraints on production, storage or transportation and all lead times are assumed constant.
9) A stage may hold stock of a particular item at a facility if it is not cheaper to hold it anywhere else. As the retailers are closer to the point of consumption and do not have mass production capabilities, it is cheaper to hold items at the central production facility than the retailers $h_0^k < h_i^k$.
10) Customization of a generic item k, should never occur if there is excess inventory of item k. Accordingly, $s_0 - h_i^0 \geq s_k - h_i^k - f_i^k$ for *i=1,2,…,N.*
11) It is never optimal to have excess inventory of the generic item and at the same time have shortage of a customized item k. Accordingly, $s_0 - h_i^0 \geq r_k - p_i^k - f_i^k$ for *i=1,2,…,N.*

12) Transshipment prices are independent of demand quantities and inventory levels at two retailers. The price does not vary with the amount of shortage or surplus at either of the locations.

13) Transshipments take place from retailers with surplus to retailers with shortage. Thus, $h_i^k < h_j^k + c_{ij}$ for all *i,j=1,2,…,N*. In preventive transshipment policies, the amount of transshipment is restricted to the main threshold values. In emergency transshipment availability is the main concern.

14) Retailer i does not transship to other retailers if there is already a shortage in the current retailer i, implying $p_j^k < p_i^k + c_{ij}$.

15) Transporting per unit item from the central production facility to the retailers is less expensive than transhipping any of the items from retailer i to j. Accordingly, $c_{ij} < t_i$ and $t_i, c_{ij} \geq 0$.

16) As the customer is the primary concern for operations, backordering an item per unit time is much expensive than holding an item per unit time or customizing a generic item at a specific item request instance $p_i^k > c_{ij} > f_i^k$ and $p_i^k, f_i^k, c_{ij} \geq 0$.

4.6 Overview of operations at the central production facility

Five different systems will be defined to establish the overall effect of postponement in an inventory-production-distribution context. The five systems will be detailed in the sections to follow, however the important decision making process between the central production facility and the retailers is explained in order to give a generalization of the systems that will be worked with. As adapted from Verrijdt and de Kok (1996) and Lagodimos and Koukoumiaslos (2008), the stochastic behaviour of the inventory variables are critical in the assessment of system performance. These will be defined in brief to create an understanding of the common working pattern of the systems.

The system will be defined at an arbitrary time interval $[t-L_0, t+L_i]$ which is the time interval before the replenishment of the central production facility and after the replenishment at the retailer.

At $t-L_0$, at the beginning of the period the central production facility echelon inventory position is raised to S_0. The echelon net inventory for the central production facility and the sum of all the retailer's inventory positions can be summarized as follows:

$$U_0(t) = S_0 - D_0(t-L_0, t+L_i) \quad \textbf{(8)}$$

and

$$J_R(t) = Min\left[U_o(t), \sum_{i=1}^{N} S_i\right] \quad \textbf{(9)}$$

The sum of the retailer's inventory positions $J_R(t)$ describes the aggregate retailer echelon inventory level. To ration the items appropriately we can utilize a rationing function q_i to describe the rationing for retailer i respectively. Accordingly then the items will be rationed such that $J_i(t) = q_i\left[J_R(t)\right]$ where

$$\sum_{i=1}^{N} q_i\left[J_R(t)\right] = J_R(t) \quad \textbf{(10)}$$

the central production facility rations the appropriate quantity of item k to the respective retailers i.

The net inventory at the retailers before and after demand realizations thus become:

Before demand realization: $U_i(t+L_i) = J_i(t) - D_i(t, t+L_i-1)$. **(11)**

After demand realization: $I_i\ (t+L_i) = J_i(t) - D_i(t, t+L_i)$. **(12)**

After rationing at some period t, the inventory position of any one retailer becomes:

$$J_i(t) = S_i - q_i \max\left[0, D_0(t-L_0, t+L_i) - \Delta\right], \text{ where } \Delta = S_0 - S_R \text{ and } \sum_{i=1}^{N} q_i = 1. \quad \textbf{(13)}$$

To further illustrate the situation, we have the following sequence of events taking place:

Every R_0 periods, the echelon inventory position of the central production facility is raised to S_o by a replenishment order generated by an authority at the central production facility. The central production facility allocates the system orders at the end of its replenishment lead time in order to pool the risk over the outside supplier lead time. This has been proven to be an effective strategy as mentioned in Schwarz (1989). Thus, the items are allocated to the retailers after being converted to customized items and not prior to it. Since the central production facility uses a periodic *(R, S_o)* policy, at the beginning of every review period its echelon inventory position is increased to an order-up-to level S_o. For the order to be allocated at time t=0, the order is initiated at t- L_0. Accordingly, the echelon stock of the central production facility, defined as the sum of inventory positions of all retailers and the physical stock at the central production facility's stocking point at t=0 is denoted as

$$S_o - D_0(0, L_0) \ , \quad \textbf{(14)}$$

which incorporates the stochastic demand instances at the retailers within the replenishment lead time.

Accordingly one of the following two cases may occur:

a) The central production facility's stock is sufficient to satisfy the orders from the retailers at time L_0.
b) The central production facility's stock is not sufficient to satisfy orders from the retailers at time L_0.

Case (a) occurs at t=0 if the amount in (14) exceeds $\sum_{i=1}^{N} S_i$ (sum of the order-up-to levels of the retailers), then all of the retailers are able to raise their echelon inventory position to their order-up-to levels. Thus,

$$D_0(0,L_0) \leq \Delta \Rightarrow J_i(t) = S_i \qquad \forall i . \qquad \textbf{(15)}$$

However if (15) is less than $\sum_{i=1}^{N} S_i$, then it is impossible to raise the inventory position of all retailers to S_i. The echelon stock of the central production facility will be lacking the total requirements of the retailers by an amount equal to

$$\sum_{i=1}^{N} S_i - (S_0 - D_0(0,L_0)) = (D_0(0,L_0) - \Delta) , \qquad \textbf{(16)}$$

and has to be accordingly rationed among the retailers. The inventory positions of the retailers can accordingly be summarized as follows:

$$D_0(0,L_0) > \Delta \Rightarrow J_i(t) = S_i - q_i(D_0(0,L_0) - \Delta) \quad \forall i . \qquad \textbf{(17)}$$

4.7 Dynamics of the systems analyzed

The retailers replenish their inventories (generic or customized) from the central production facility and the central production facility from an uncapacitated supplier within the five different systems implementations. The differences among the systems are due to the type of inventory held and how inventory is distributed within the systems. System1 and System 2 allow customization only at the central production facility, whereas System 3 and System 4 allows generic items to be sent to the retailers, thus customization capabilities are given to the retailers. System 5 allows both generic and customized items at the retailers. System 2, 4 and 5 are also given transshipment privelages among the same echelon or retailers. All storage and transportation capacities are unlimited and transportation of an item from the central production facility to the retailer occurs after orders have been placed from the respective lower-echelon retailers. The ultimate aim is to manage the place and timing of the deliveries in order to better manage total cost and increase customer responsiveness. System distinctions will be best observed under similar operating characteristics. The aim is to differentiate which system works better under predefined experimental settings. The work of Johnson and Montgomery (1974) and Silver *et.al.* (1998) have been taken as reference.

Accordingly, in all of the systems since the raw material is never out of stock, due to an uncapacitated resource assumption, the problem is more of controlling the generic (semi-finished) and customized (finished) item inventories within the supply chain. Since, raw material conversion is unique to the central production facility and an inevitable part of the system, it is important to manage and delegate it such that system imbalances are avoided.

Every review period, replenishment orders for differenent inventory items are placed by the retailer. Since the inventory requested among any of the five system implementations maybe either generic or customized, the inventory levels of these types of items are observed in reference to the central production facility. In either case, if the requested item is not available in the required amounts at the central production facility it has to be rationed among the retailers.

If a replenishment order for *Q(t)* units of finished items are placed at the retailers, then the amount of available inventory available at the production facility should be investigated to initialize production.

Accordingly, the amount of net generic inventory at the end of period t, is described to be:

$$IG(t) = IG(t-1) + XR(t) - Q(t) = IG^{+}(t-1) - IG^{-}(t-1) + XR(t) - Q(t)\,, \qquad \textbf{(18)}$$

where $IG^{+}(t)$ is the on-hand generic inventory at the central production facility and $IG^{-}(t)$ is the backorder level of the generic inventory at the central production facility.

Accordingly, the amount of items available in the central production facility and ready to be assigned to the retailers is summarized as follows:

$$Y(t+\tau_i) = \begin{cases} Q(t) + IG^{-}(t-1); & IG(t) \geq 0 \\ \\ XR(t) + IG^{+}(t-1); & IG(t) \leq 0 \end{cases} \qquad \textbf{(19)}$$

Accordingly, if *Y(t)* is enough to satisfy the order-up-to levels at the retailer, then it is duely distributed to the retailers. Otherwise, the rationing policy is implemented.

Thus, the ordering decision at the start of period t first affects the customized items inventory in period t+$\tau_i + D_0$, thus the net inventory available at the central production facility at the end of period t become:

$$F_k(t+\tau_i + D_i^k(t)) = F_k(t-1) + \sum_{r=t}^{t+\tau_i-1} Y_k(r) + \sum_{i=t}^{t+D_0-1} XR(t) + Q(t) - \sum_{r=t}^{t+D_0+\tau_i} D_i^k(r)\,. \qquad \textbf{(20)}$$

Accordingly, the ordering decision at the central production facility affects the generic inventory in period t+τ_0, thus at the end of the period the amount of net generic inventory available in the system becomes:

$$IG(t+\tau_0) = IG(t) + \sum_{r=t+1}^{t+\tau_0} (XR(r) - Y(r)) \quad \textbf{(21)}$$

which summarizes the inventory balance at the central production facility according to generic and customized item distinction respectively.

4.8. Order of events in the five systems

Each period the following sequence of events take place. The order has been considered in consideration to the functions of the central production facility and the retailers separately using flowcharts.

Time is divided into periods of equal length as defined in the review interval.

1) Retailers request replenishment for customized/generic items from the central production facility. Orders have to be placed before demands are realized, thus the allocation of multiple items to retailers is initiated prior to the demand realization.
2) The central production facility orders raw material from the supplier.
3) Orders placed earlier by the central production facility *L* periods earlier from the supplier arrive at the central production facility, and then they are either converted to customized items or held as generic items. According to the order size from the retailers, the items are sent to the retailers in full or are rationed among the retailers.
4) Retailers receive replenishment after a certain lead time.
5) Customer demands occur at each retailer.
6) If items are available at the time of customer requests at the retailers, order is completely fullfilled, otherwise the orders are backordered. The retailer may satisfy all requests directly or satisfy part of the request and backorder the remaining portion which was not available on-hand at the respective retailer.

7) The retailers may utilize a transshipment policy if allowed by the relevant system.

For each retailer and the central production facility, the on-hand inventory, outstanding backorders, on-order inventory and in-transit inventory are calculated before demand in period t (between events 4 and 5). Cachon and Fisher (2000) note that the central production facility's on-order inventory is always zero, because the supplier always ships inventory immediately due to unlimited supply. However, a retailer's on-order inventory can be positive when the central production facility cannot fill the retailer's order completely.

4.8.1. Order of events in System 1

The order of events for System 1 can be seen in Figure 4.1 for the central production facility and Figure 4.2 for an individual retailer. Value-adding processes are conducted at the central production facility where the raw material is converted to generic items and then to customized items. The retailers receive only customized items. The average total cost of the central production facility and an individual retailer i, following an order up-to S_i^k periodic review policy, with re-order point s_i^k, consists of several cost items. The following main cost items as adapted from Monthatipkul and Yenradee (2008) are: ordering cost, holding cost at the central production facility/retailers, backorder costs at the retailers, transportation costs from the central production facility to the retailers and transshipment costs if system permits. Purchasing costs are considered as sunk costs, moreover, salvage and revenue attained from the sale of an item is disregarded.

Cost Performance of the System

The aim is to minimize the total expected operational costs for the two-echelon supply chain over a time interval of [0, T] as follows:

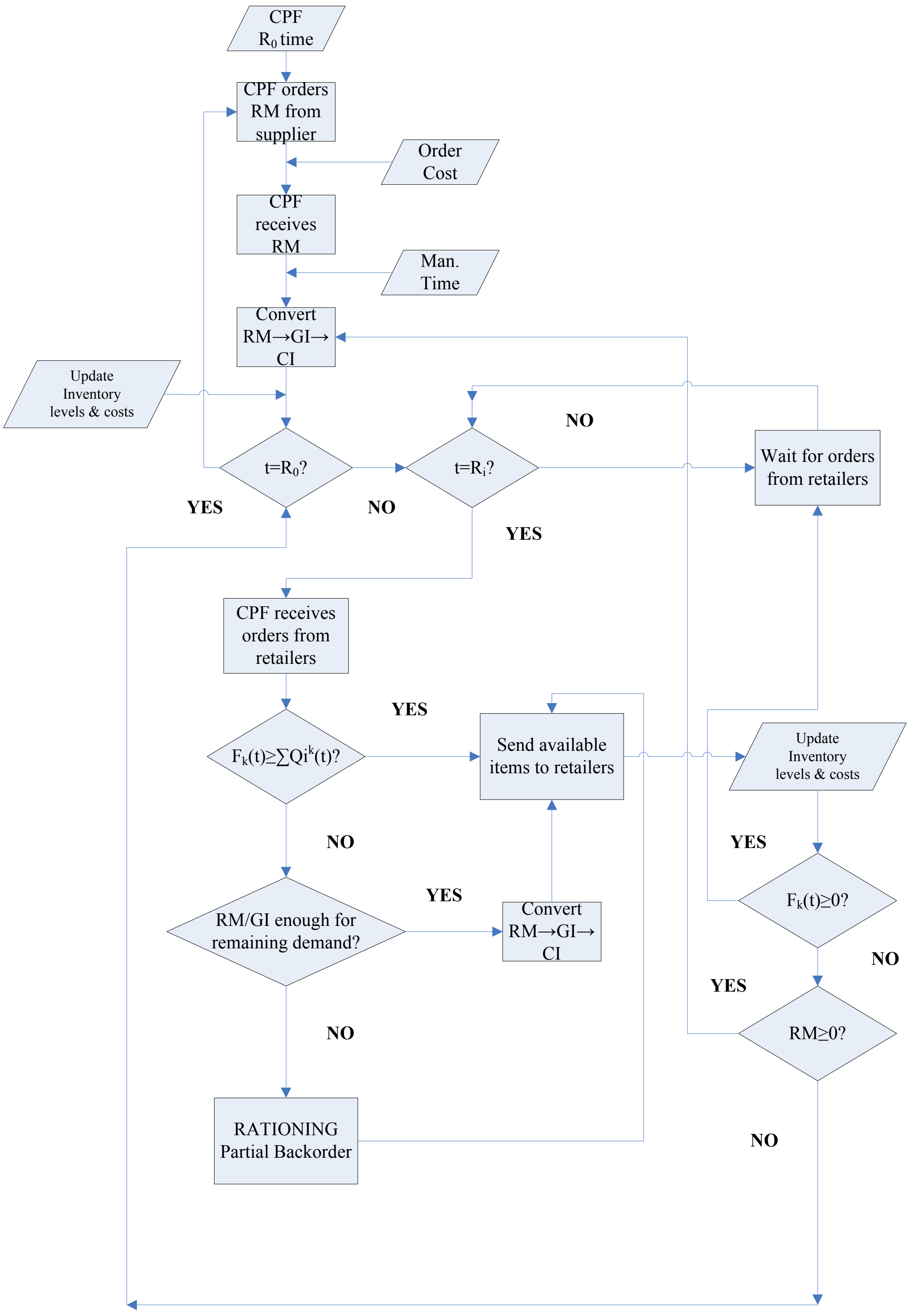

Figure 4.1 System 1: Flow of customized items through the central production facility

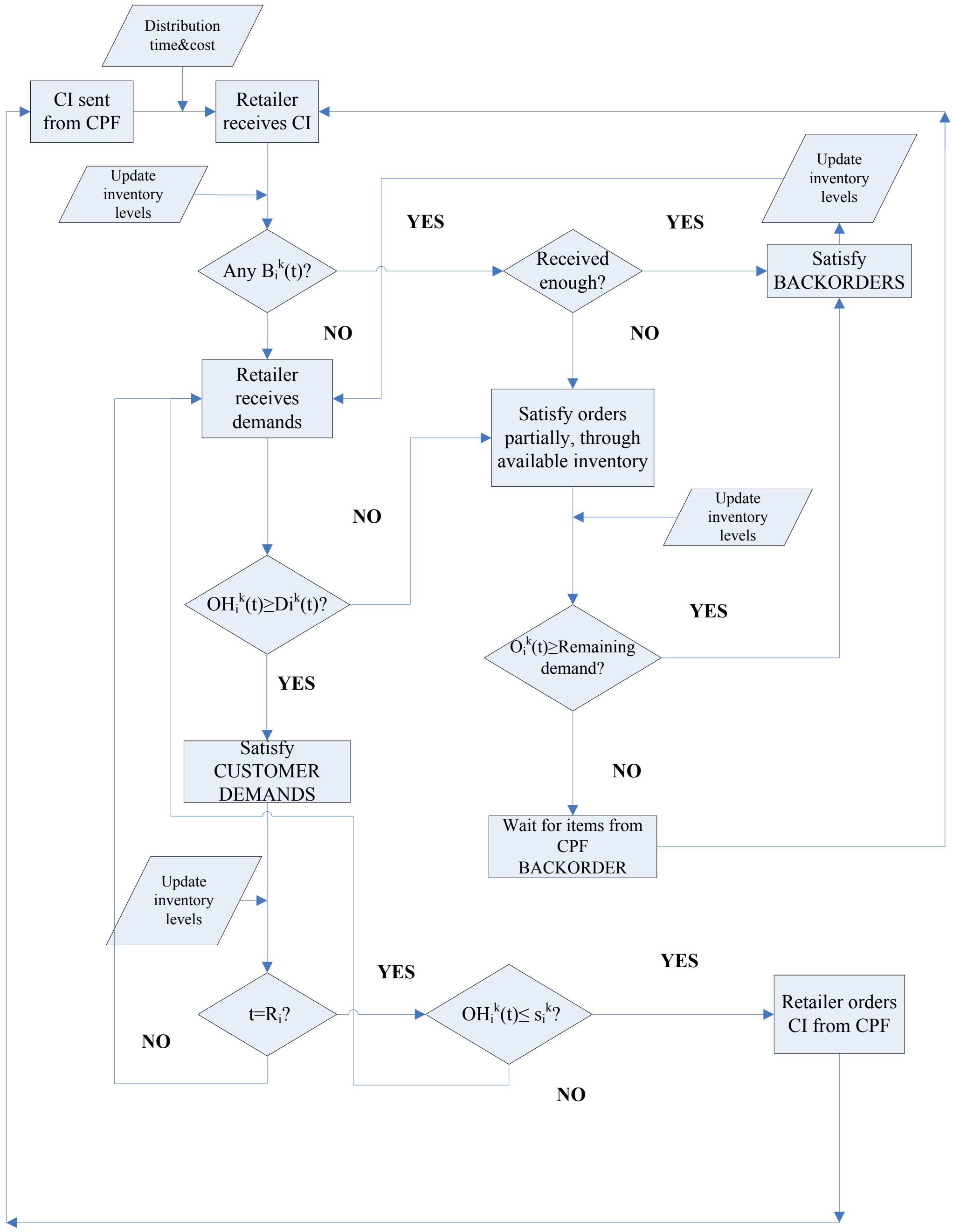

Figure 4.2 System 1: Flow of customized items through the retailers

$$TC = \sum_{k=0}^{M}\sum_{i=0}^{N} h_i^k \int_{t=0}^{T} OH_i^k(t)dt + \sum_{k=1}^{M}\sum_{i=1}^{N} p_i^k \int_{t=0}^{T} B_i^k(t)dt + \sum_{t=0}^{T}\sum_{i=1}^{N} t_i T_{it} + \sum_{t=0}^{T}\sum_{k=1}^{M} f_0^k Y_t^k + \sum_{t=0}^{T}\sum_{i=0}^{N} A_i B_{it} \quad \textbf{(22)}$$

Accordingly, the on-hand and backorder functions imply that $OH_i^k(t) = \max\{I_i^k(t), 0\}$ and $B_i^k(t) = \max\{-I_i^k(t), 0\}$ respectively.

At the central production facility, the holding cost is calculated based on the ending inventory, because inventory decreases at the beginning of a period and remains constant during the period. At the retailers, the beginning and ending inventory is critical, as it decreases due to the arrivals of customers which may occur any time during period t. The first two terms in the total cost function represent the holding and backorder costs incurred during the simulation time. The third term expresses the transportation costs incurred in sending an item from the central production facility to the retailer. The fourth term reflects the customization that is incurred at the central production facility. The first system does not allow any customization at the retailers thus all customization is handled at the central production facility. The last expression represents the ordering cost for the retailers and the central production facility. This is also an important concern in respect to the total cost as the frequency of requests is increased. It may discern the difference between holding more inventory rather than ordering more frequently in the system.

4.8.2 Order of events in System 2

Transshipment is an effective policy which enhances collaboration among retailers in case of shortages by allowing lateral inventory redistribution. It is a strategy where retailers at the same echelon are in coordination and exchange customized end items to meet an immediate (or future) need (Reyes, 2006). Thus,

rather than relying on a direct delivery from the prior echelon, items are transferred among retailers at the same echelon level.
In the first system the retailers manage their inventory independently, there is risk of inventory imbalance, due to the variance in customer demand for various items. Imbalance is inevitable with stochastic demands, as some retailers may face shortages whereas others may have more inventory on hand than necessary.

In System 2, at the beginning of each period all retailers release orders aimed at restoring their inventory position to the order-up-to level S_i^k . If there is sufficient inventory at the central production facility, all the orders are completely satisfied. If the inventory for end items is insufficient it is rationed among the retailers. Thus, the amount of inventory available to the retailers may not be enough to satisfy the whole demand of customers at a particular retailer i. In such instances transshipment is allowed within the system. A transshipment policy is implemented either as a reactive (emergency) or a proactive (preventive) approach in the experimental settings.

With regard to the common timeline defined in the previous system, events 1-6 are similar to those in System 2. However, after demand realizations, if there is not enough item k at retailer i, the retailers have a chance to request the corresponding item from other retailers, utilizing emergency transshipment. Otherwise, it has a chance to balance inventory levels at retailer stocking locations through preventive transshipment any time before the receipt of items from the central production facility. Herer *et. al.* (2006) points out that optimal transshipment strategies for different retailers need to be determined on a period-by-period basis, whereas an order-up-to quantity has to be found only once for the entire system. The flow of operations for this system is given in Figure 4.3 and Figure 4.4, seperately for the central production facility as well as the retailers. Figure 4.4a and Figure 4.4b is also distinctively differentiated according to transshipment type: preventive and emergency.

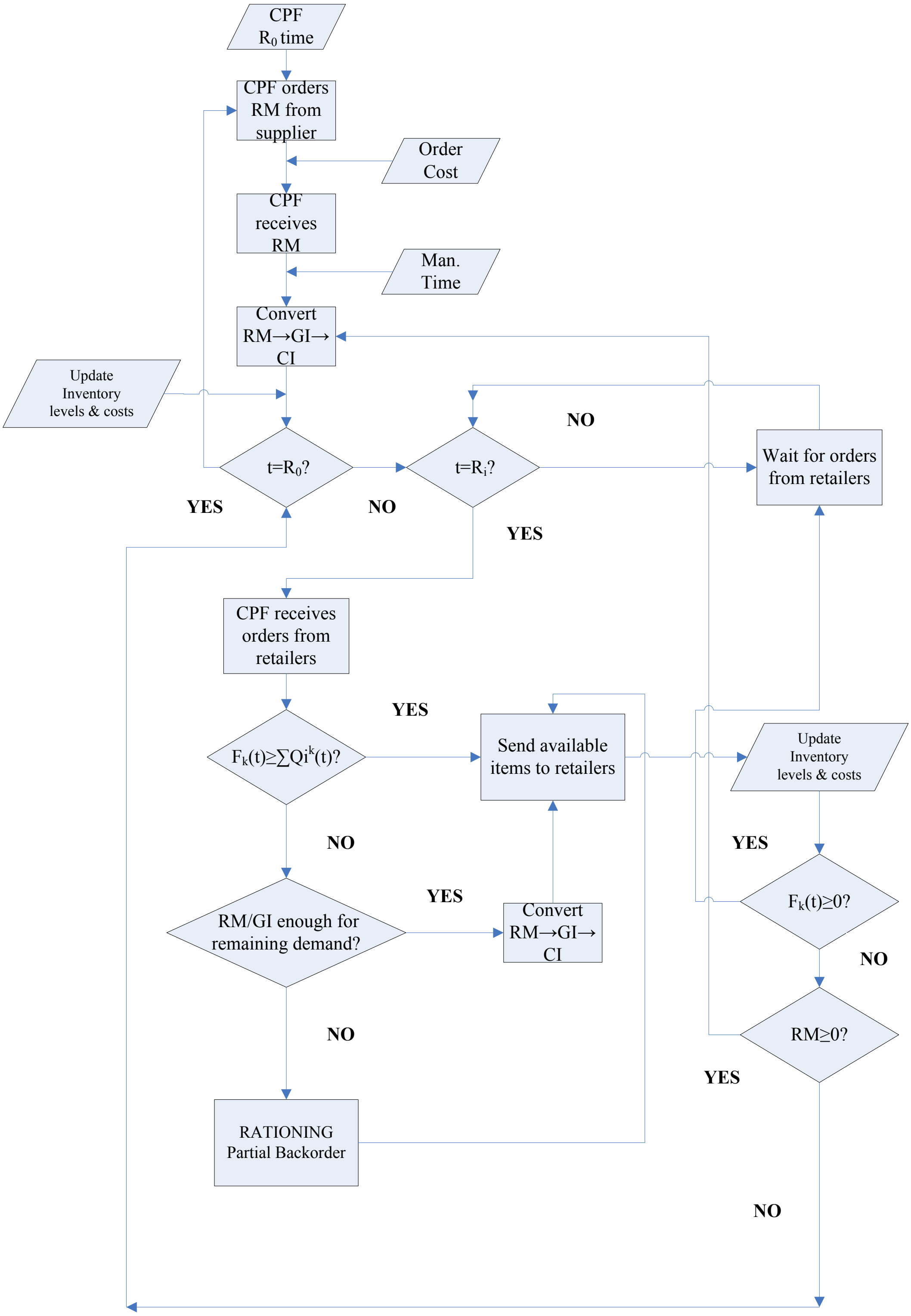

Figure 4.3 System 2: Flow of customized items through the central production facility

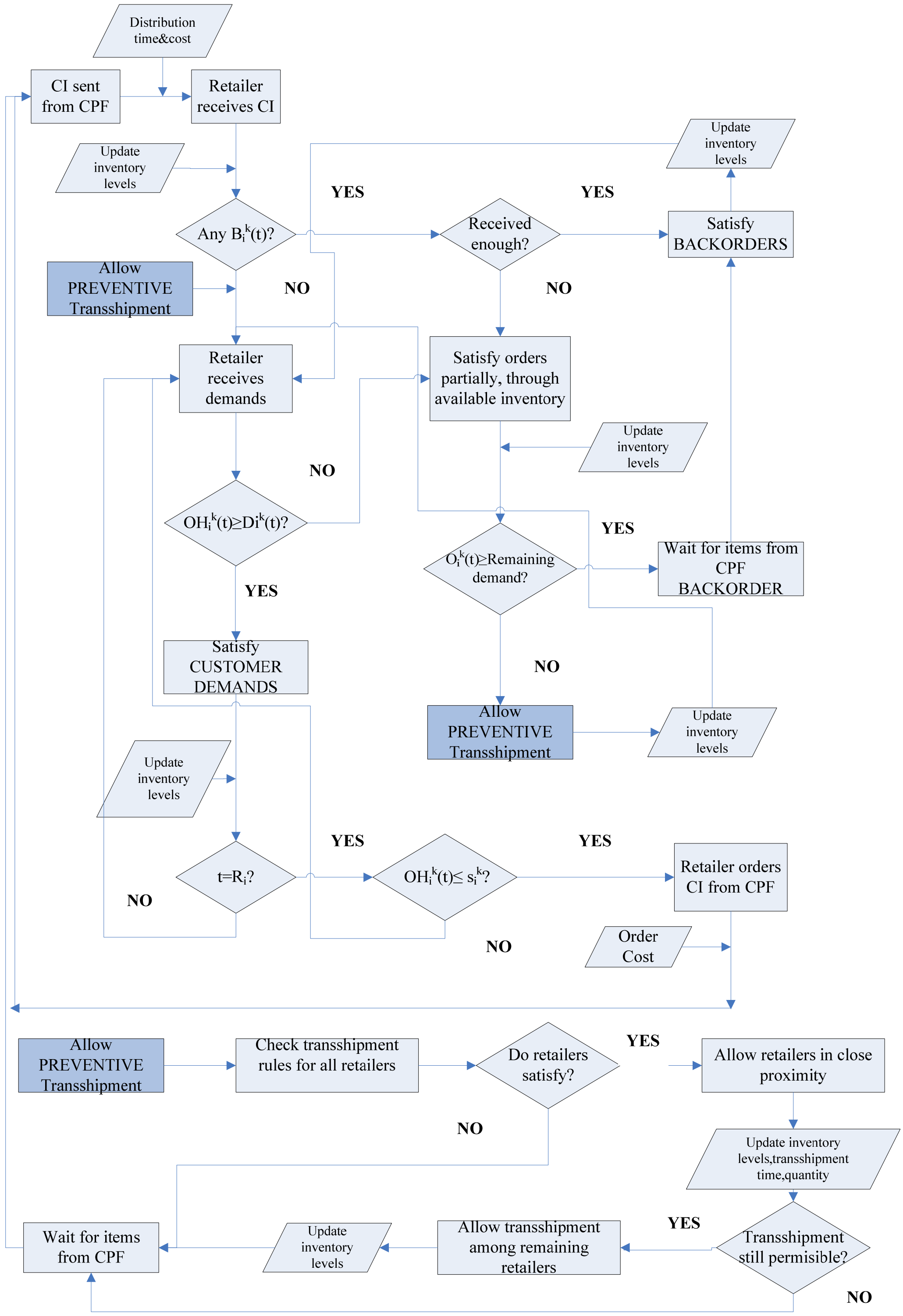

Figure 4.4a System 2: Flow of customized items with preventive transshipment at the retailers

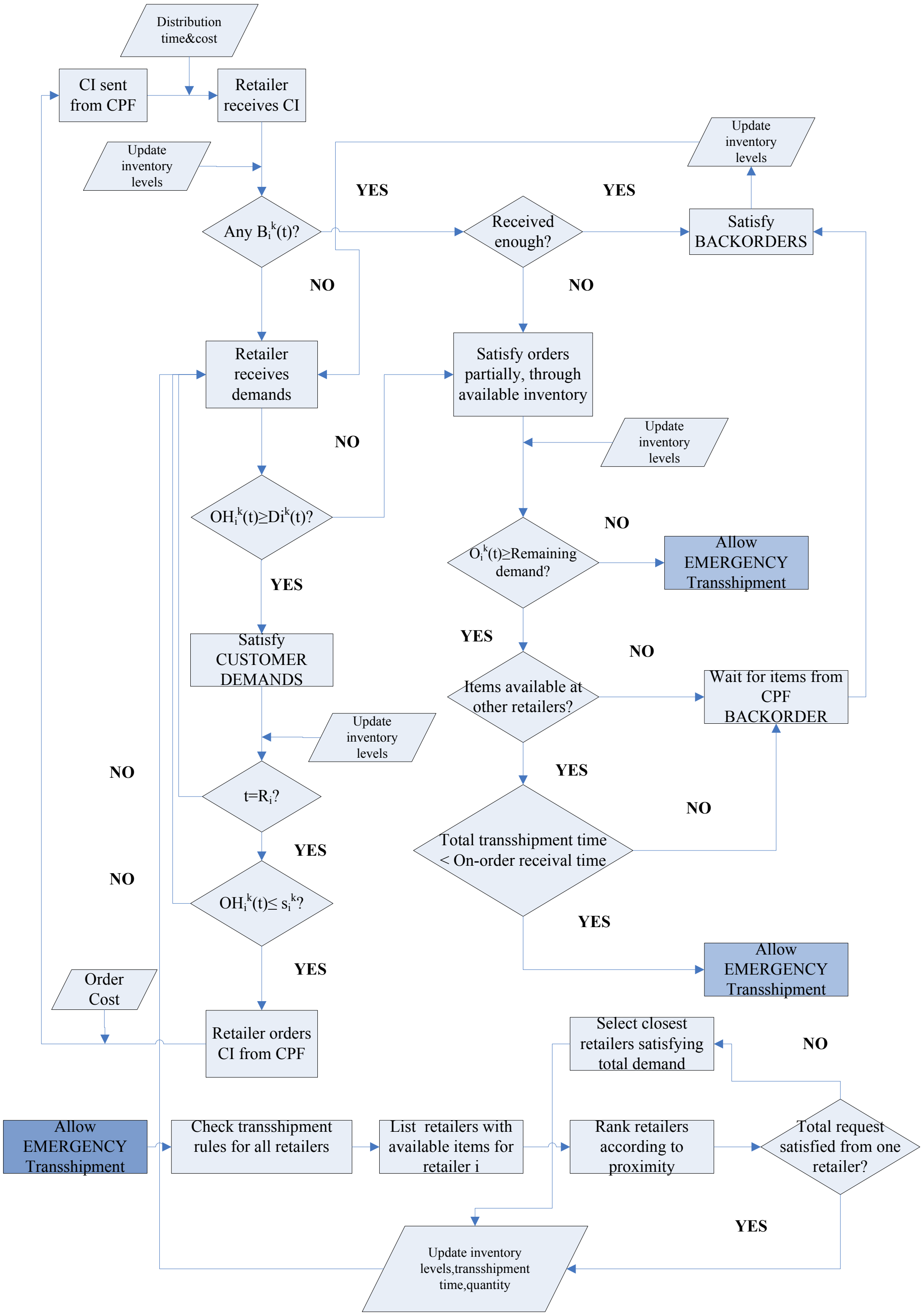

Figure 4.4b System 2: Flow of customized items with emergency transshipment at the retailers

4.8.2.1 Modelling the transshipment policy

Tagaras and Cohen (1992) and Tagaras and Vlachos (2002) have defined various policies that are commonly utilized in transshipment operations. The allocation policy is based on the adoption of either preventive or emergency transshipment. Based on the timing of customer demands, either inventory position or net inventory position is utilized in the implementation of a transshipment policy. The work of the above mentioned authors have been adapted in defining transshipment implementations within the systems that utilize transshipment in this work.

First, let us define:

SS_i^k : Represents the target inventory position, that retailer i wishes to maintain of item k before transhipping a quantity X_{ijt}^k of item k to retailer j from retailer i. In the system settings this is equal to the safety stock level at each retailer i for different item's k.

t_{ij}^k: Threshold inventory level of item k that retailer j would like to reach but not exceed after receipt of the transshipment X_{ijt}^k from retailer i. This is enforced in order to avoid system imbalance among the retailers. The re-order levels at the retailers have been taken as the distinctive threshold levels.

Allocation according to net inventory position

If the timing of operations is disregarded in transshipment implementations, evaulation of allocation decisions are done according to the net inventory positions at the respective retailers. Allocation according to net inventory position is carried out for representative two retailers i and j as follows:

If $IN_i^k(t) > SS_i^k$ and $IN_j^k(t) < t_{ij}^k$ then

$$X_{ijt}^k = [\ \min\{IN_i^k(t) - SS_i^k ; t_{ij}^k - IN_j^k(t)\}\ ]^+ \text{; otherwise } X_{ijt}^k = X_{jit}^k = 0 \quad \textbf{(23)}$$

In such systems it is assumed that $SS_i^k \leq t_{ij}^k \leq S_i^k$.

Two possible outcomes are present in this evaluation:

CASE 1a: In emergency transshipment, transshipment takes place when the retailer faces an immediate shortage in the current period. Thus, the threshold levels at the retailers are disregarded because there is already an imbalance (shortage) at one of the retailers.

CASE 2a: If $t_{ij}^k \neq 0$, then lateral transhipment from retailer i to j takes place even if retailer j does not have a shortage. The amount of items to be transshiped is restricted in order to avoid system imbalance. Preventive transshipment is possible at any time of the simulation run, where the conditions in equation 23 are satisfied.

Allocation according to inventory position

Inventory positions of the retailers are utilized if time is a critical concern in transshipment operation decisions. Foremost, if the on-order inventory will arrive later than a transshipment policy, the amounts to be transshipped among the retailers are determined as a function of inventory position, rather than net inventory position as done previously. This is to better manage the receipt time and amount of inventory at the retailers. Otherwise, the net inventory position is a good estimate to the amount to be transshipped as mentioned previously. If inventory position is adopted, the allocation is done for representative retailers i and j as follows:

If $IP_i^k(t) > SS_i^k$ and $IP_J^k(t) < SS_j^k$ then

$X_{ijt}^k = [\ \min\{IP_i^k(t) - SS_i^k; SS_j^k - IP_j^k(t); IN_i^k(t); t_{ij}^k - IN_j^k(t)\}]^+$; otherwise

$X_{ijt}^k = X_{jit}^k = 0$ where $[X_{ijt}^k]^+ = \max(0, X_{ijt}^k)$ **(24)**

Similarly, two cases are also possible for this assessment:

CASE 1b: If the threshold levels at the retailers are assumed zero, the transshipment takes place when the retailer faces an immediate shortage in the current period. This is the same as an emergency transshipment.

CASE 2b: If $t_{ij}^{k} \neq 0$ then preventive transshipment maybe enforced, where transshipment takes place as a function of inventory availability. However, in preventive transshipments timing is not a critical concern, thus, this rule has not been enforced in our system implementations and calculation is carried out for net inventory position, as in Case 1b respectively.

Cost Performance of the System

In either of the cases utilizing net inventory position or inventory position the quantity X_{ijt}^{k} at any time is limited to the physical availability of the stock. In case of ties, the allocation rules defined by Banerjee et. al. (2003) is utilized. In order to break tie rules in cases where two retailers are facing similar conditions Banerjee et al. (2003) enforces the following rules:

1) Rank the excess locations, with respect to item type and quantity.
2) Rank the locations with shortages, priority is given to maximum amount of shortage faced within a retailer.
3) Transship the appropriate quantities to satisfy the shortage. More than one retailer may satisfy the need of a single retailer.

Continue until either there is no shortage or excess at any of the retailers. In order to derive the total costs incurred on the system for this implementation, the inventory level at retailer i of item k immediately after transshipments and demand satisfaction is defined as $IT_{i}^{k}(t)$ and reflected in the formulation as follows:

$$IT_i^k(t) = S_i^k - \sum_{j=1}^{N} X_{ijt}^k + \sum_{j=1}^{N} X_{jit}^k - D_i^k(t) \qquad \textbf{(25)}$$

where X_{ijt}^k is the amount transshipped from retailer i to retailer j of item k. Accordingly IT_i^k maybe positive or negative and accordingly satisfy the following rules for the retailers as follows: $OH_i^k(t) = \max\{IT_i^k(t), 0\}$ and $B_i^k(t) = \max\{-IT_i^k(t), 0\}$ respectively.

For the central production facility, the on-hand items are a function of available customized items waiting to be allocated to the respective retailers and not a function of inventory level at the retailers, as previously defined in System 1 implementation. Thus the realized cost of the system in a time period [0,T] is as follows:

$$TC = \sum_{k=0}^{M} h_0^k \int_{t=0}^{T} OH_0^k(t)dt + \sum_{k=1}^{M}\sum_{i=1}^{N} h_i^k \int_{t=0}^{T} OH_i^k(t)dt + \sum_{k=1}^{M}\sum_{i=1}^{N} p_i^k \int_{t=0}^{T} B_i^k(t)dt +$$
$$\sum_{t=0}^{T}\sum_{i=1}^{N} t_i T_{it} + \sum_{t=0}^{T}\sum_{k=1}^{M} f_0^k Y_t^k + \sum_{t=0}^{T}\sum_{i=0}^{N} A_i B_{it} + \sum_{t=0}^{T}\sum_{i=1}^{N}\sum_{j=1}^{N}\sum_{k=1}^{M} c_{ij} X_{ijt}^k \qquad \textbf{(26)}$$

The ideal transshipment/pooling policy is based on information about the timing and quantity of all outstanding orders at both retailers. As seen above, the relative values of the costs will be decisive in implementing the correct action: transship, transport or hold inventory. However, evaluating the expected total cost analytically and optimizing it mathematically is intractable due to the complex relationships among the system parameters which are the demand rates, pipeline inventories and transshipment quantities, thus simulation is beneficial in such cases (Tagaras and Vlachos, 2002). Overall, the first two entries denote the holding costs at the central production facility as well as the retailers. The distinction comes from the amount of items available at the retailers which is a function of demand as well as the transshipment policy. The backorder costs are incurred at the retailers and are reflected in the third expresssion. The central production facility still holds generic and customized inventory and converts at the lower echelon so the customization cost incurred at the central production facility is also reflected in the cost function. The amount of retailer orders are critical and can be reduced due to the transshipments taking place between the retailers. Ordering costs for the central production facility and the retailers are also duely reflected. The transshipped quantities in this system are all customized items because there are no generic inventory allowed at the retailers and the cost of these items are reflected in the last expression.

4.8.3 Order of events in System 3

In System 3, the central produciton facility only produces generic items and accordingly sends these items to the retailers. The order-up-to-levels of the retailers become $S_i = \sum_{k=0}^{M} S_i^k$ due to demand aggregation. This is possible due to the fact that our assumptions state that one generic item is enough to convert any of the customized items into the requested form. Instead of customized item based assignment, the inventory to the retailers is assigned according to the total resource required for the total demand at retailer i. Since customization is carried out after the realization of demand, prior to this realization the generic items are distributed among the retailers. The rationing policy at the central production facility is the same as discussed for System 1 and 2. However, after distribution of the generic item to the retailers, the conversion is based on the demands faced at the retailers. In any instance, where two different items are requested at the same time, a tie-breaking rule is used where priority is given to the most value-adding item in the system, which is assumed to be item 1 among the M different items available. Accordingly, item M is the least costly item to be considered in the system. Within this system, item conversion is done solely at the retailers. The inventory held at the central production facility is raw material and generic item. The replenishment lead time has also been reduced, due to the fact that the order-up-to levels are now not a function of the bulk customization time at the central production facility. The re-order levels at the retailers are now not a function of customized items but are determined according to generic item requirements. The order of events for the system with postponement can accordingly be viewed in Figure 4.5 for the central production facility and Figure 4.6 for a respective retailer.

Cost Performance of the System

A critical factor in System 3 evaluation is the effect of holding generic items both at the central production facility and the retailers. Overall, coverage of the correct items is important in reducing backorder costs in the system. It is expected that there will be less backorders, as orders are handled after demand is known and initiated. This is critical in evaluating overall system performance. The system performance is affected by the holding and ordering costs at the central production facility and the retailers, backorder costs and transportation costs of the items sent to the retailers. The overall system assessment is similar to the structure in System 1. Thus, the expected total cost becomes as follows with the differentiation that customized items are not allowed to be held at the central production facility and retailers. The holding costs are a function of the generic item available at the central production facility and the retailers. Customization costs are incurred at the retailers, since item customization is not allowed at the central producton facility. Lastly, dependng on the penalty of not being able to satisfy a specific item demand, backorder cost is a function of different item type requests by the customers. Thus, the average total cost function becomes:

$$TC = \sum_{i=0}^{N} h_i^0 \int_{t=0}^{T} OH_i^0(t)dt + \sum_{k=0}^{M}\sum_{i=1}^{N} p_i^k \int_{t=0}^{T} B_i^k(t)dt + \sum_{t=0}^{T}\sum_{i=1}^{N} t_i T_{it} + \sum_{t=0}^{T}\sum_{k=1}^{M}\sum_{i=1}^{N} f_i^k Y_t^k + \sum_{t=0}^{T}\sum_{i=0}^{N} A_i B_{it} \qquad \textbf{(27)}$$

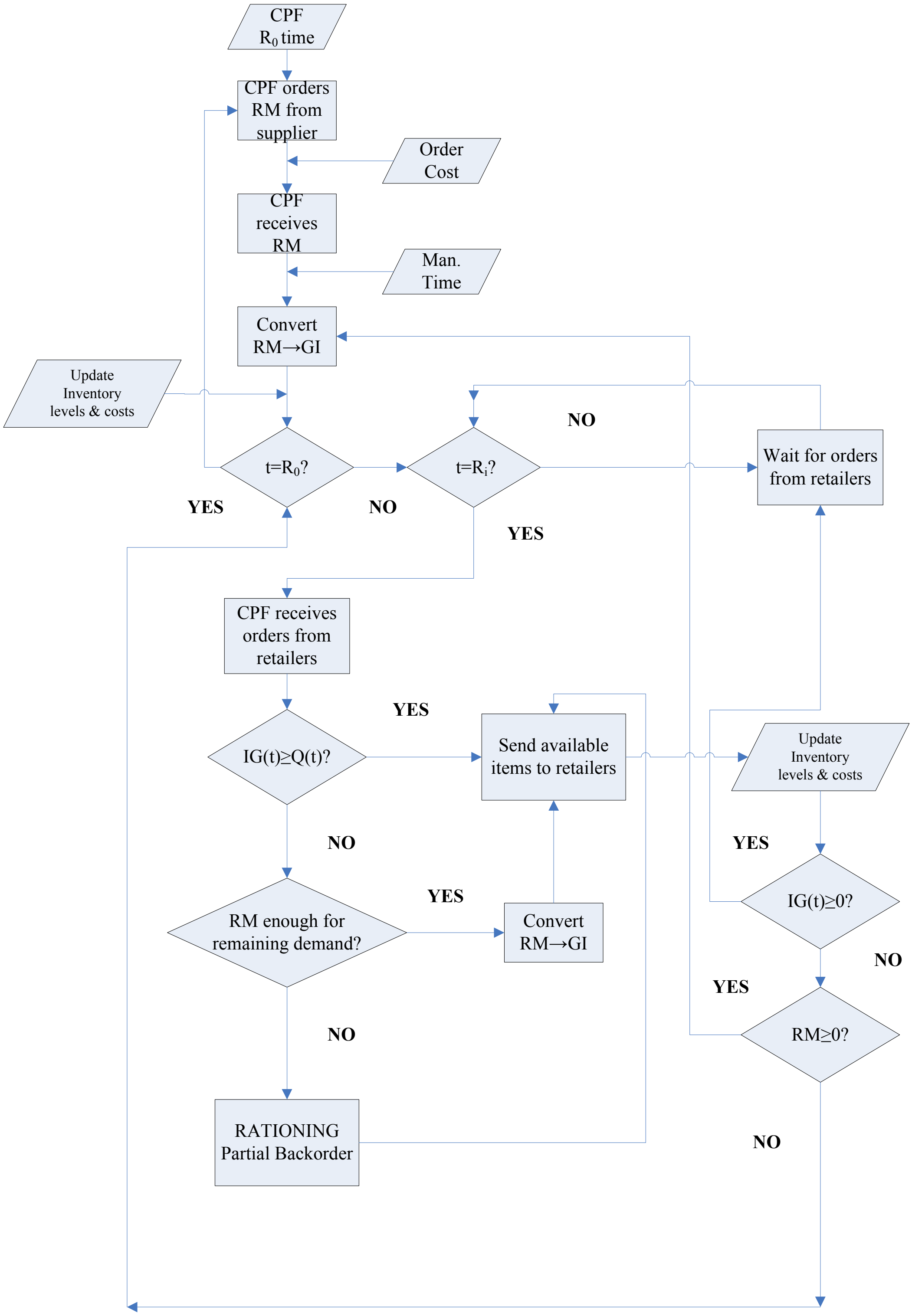

Figure 4.5 System 3: Flow of generic items at the central production facility

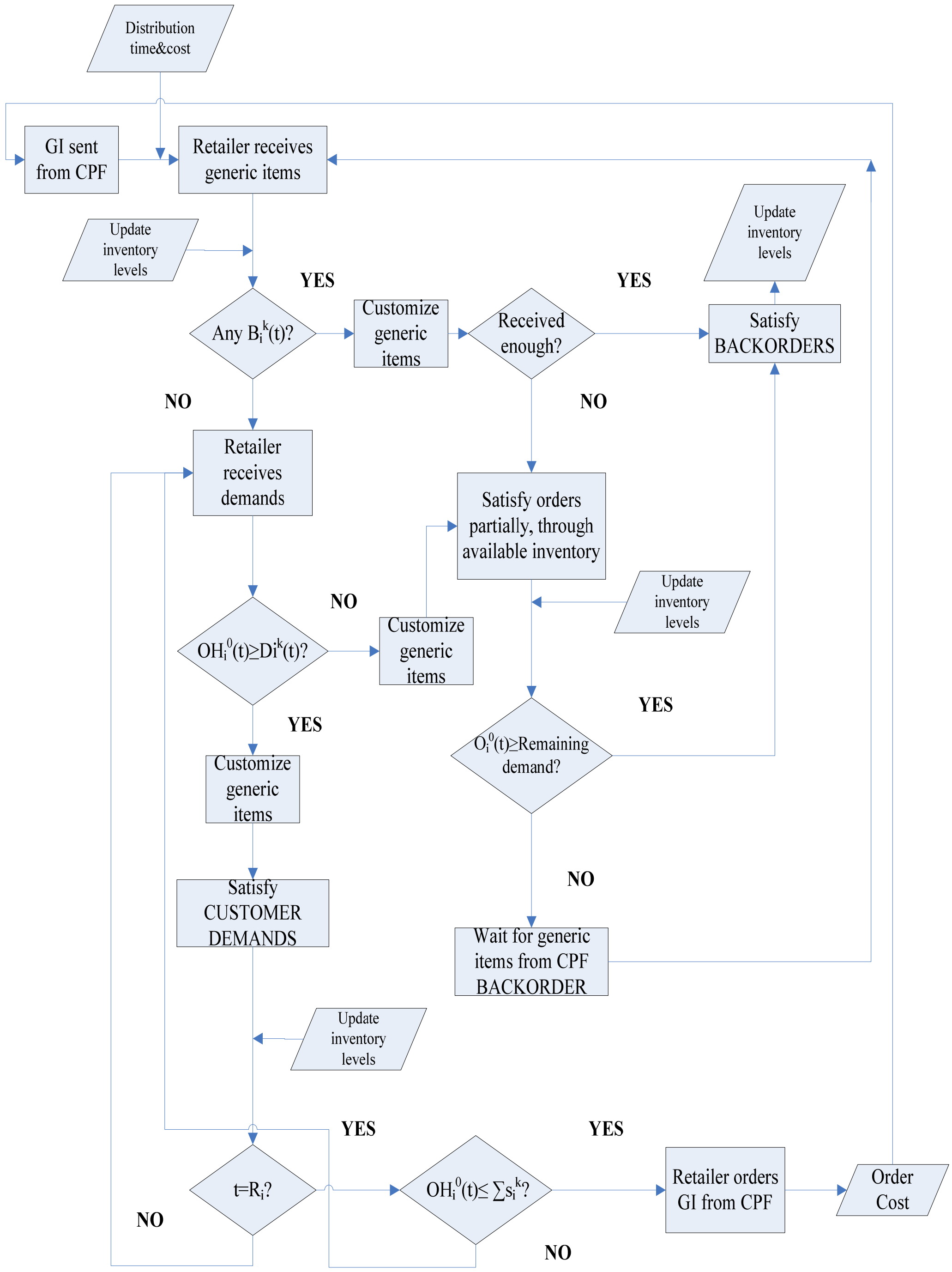

Figure 4.6 System 3: Flow of generic items at the retailers

4.8.4 Order of events in System 4

In System 4, the retailers have an extra capability in utilizing both type of postponement strategies: form postponement and transshipment. Foremost, the items are sent from the central production facility in the generic form, no customization is allowed at the central production facility. After demand realizations, items are allowed to be customized according to customer requirements. In the case where on hand generic inventory is not sufficient to satisfy retailer i demand, retailer i may request the items from retailer j using an emergency transshipment policy. In such an allocation, expected service time is an important consideration in allowing the replenishment of the items. Overall, it is assumed that the critical lead times of transportation, transshipment and customization satisfy $\tau_i < LT_{ij} < L_i$. Otherwise the next replenishment period is waited to request an item from the central production facility. In preventive transshipment, transshipments may occur at any time within simulation implementation. The decision to adopt postponement is also a matter of the timing of operations and the involvement of the customer in the process. As a distinction from System 1 and System 3 implementations logistics postponement may be incorporated early or late in the system.

As can be observed in Figures 4.7-4.8a and 4.8b, the exchange between the central production facility and the retailers are based on generic item inventories. Overall, when the items are evaluated according to the the movement of material, three different options are available as adapted from Herer *et. al.* (2006). At the beginning of the period, when demand requests and previously incurred backorders are satisfied, there may be three different ways the generic inventory may be utilized in the system: a) To satisfy the demand at retailer i immediately, b) To satisfy the demand at retailer j through transshipment (if previously mentioned transshipment conditions hold) c) To hold generic inventory at retailer i for future demand instances.

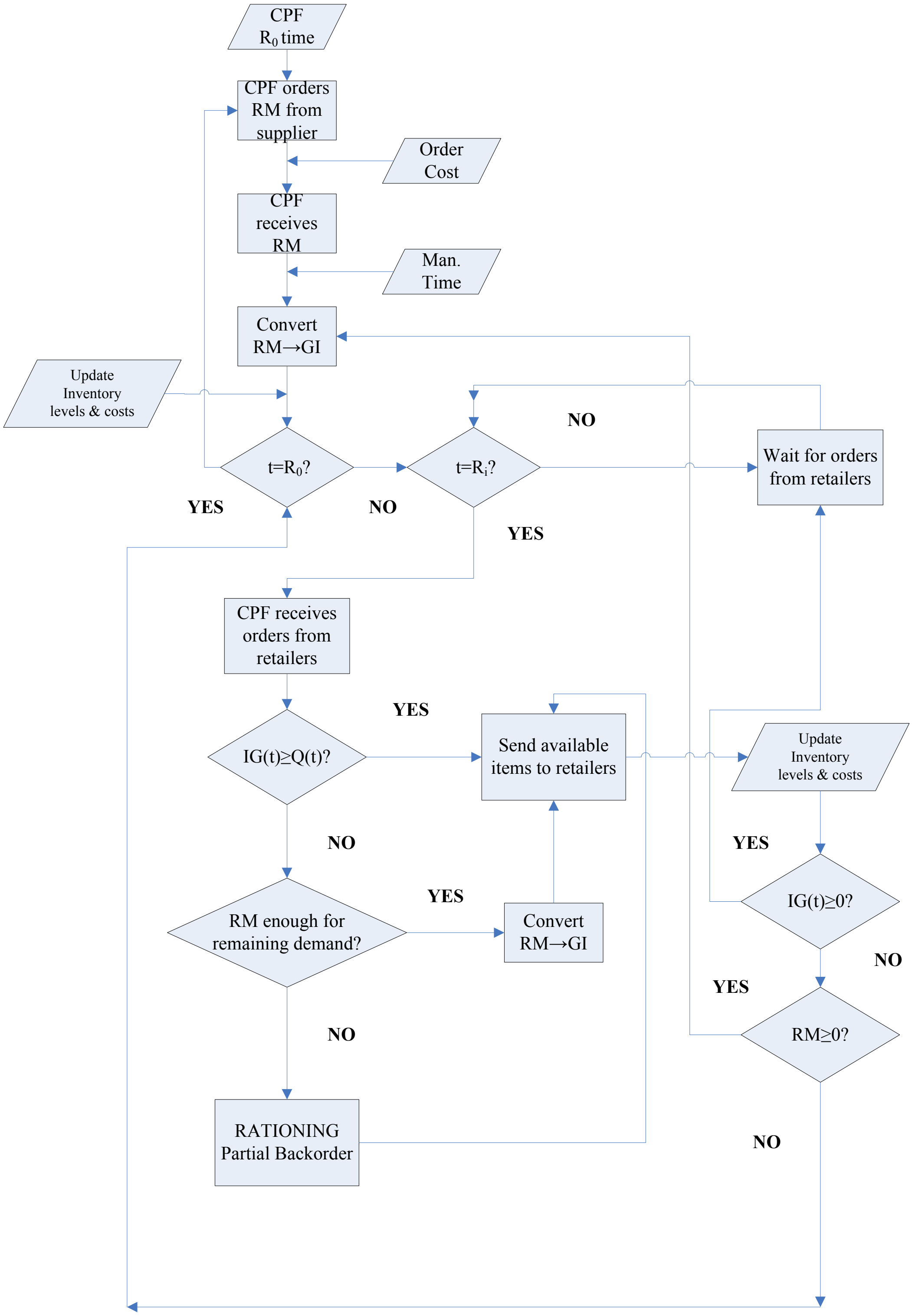

Figure 4.7 System 4: Flow of generic items at the central production facility

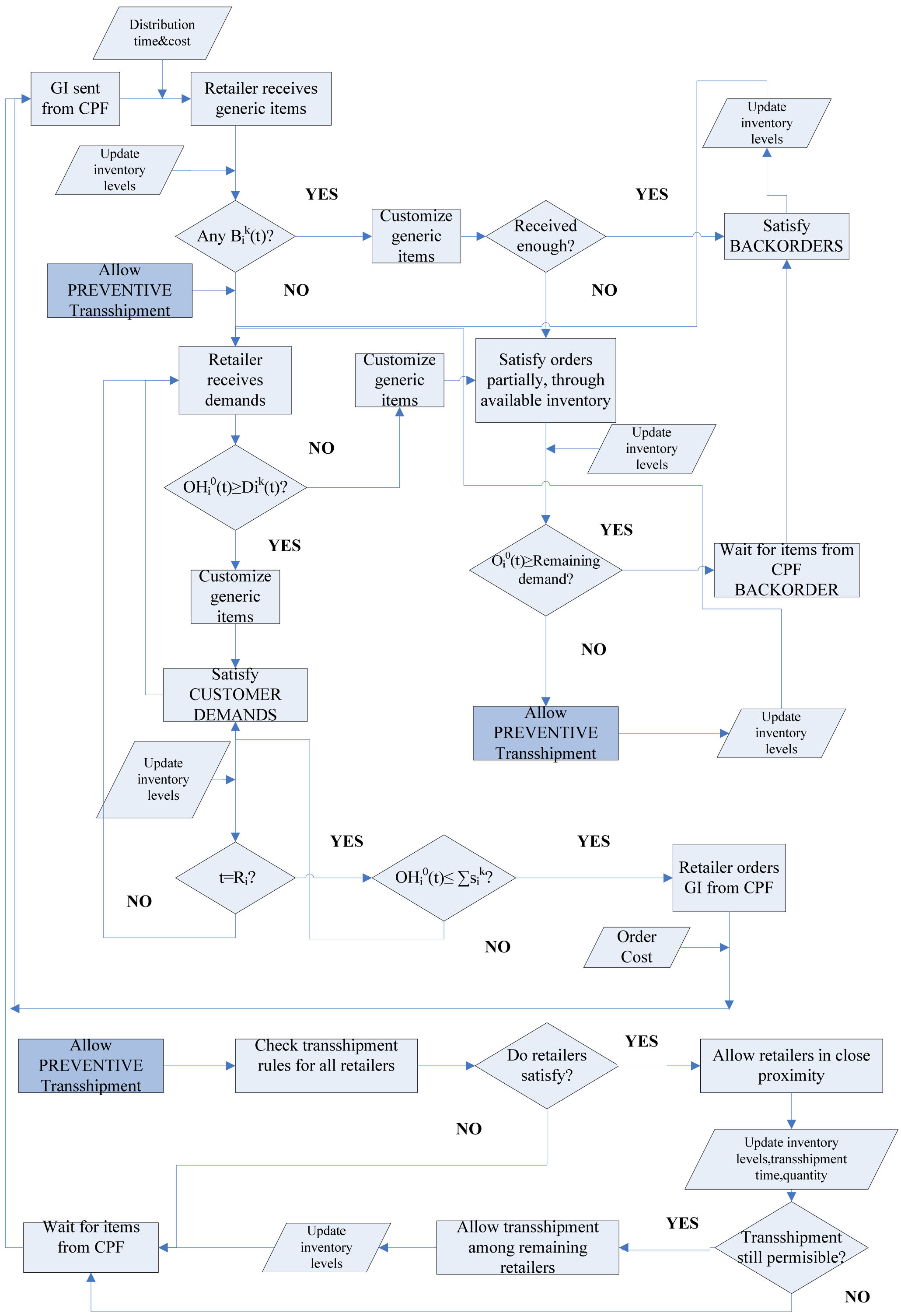

Figure 4.8a System 4: Flow of generic items at the retailers with preventive transshipment

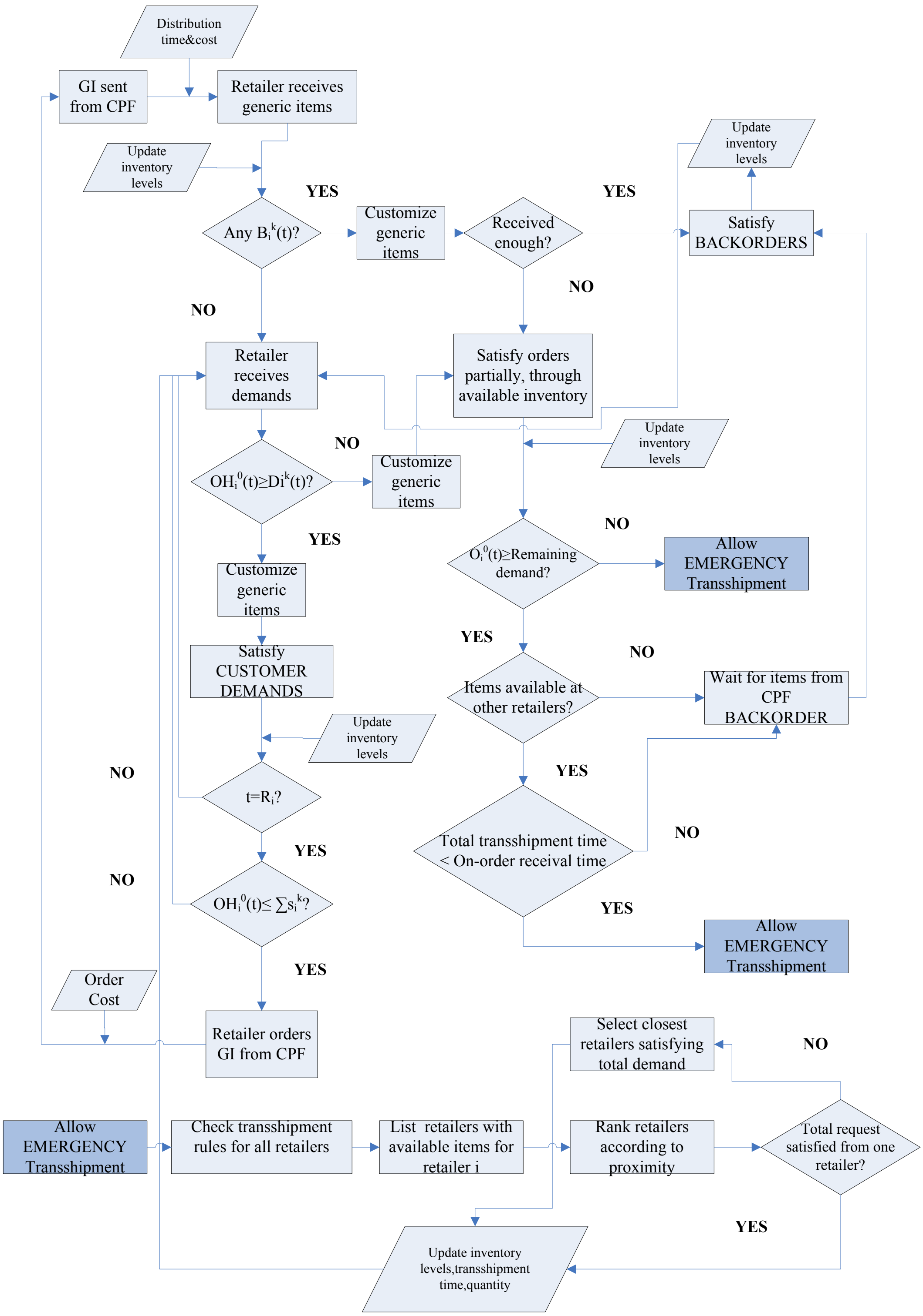

Figure 4.8b System 4: Flow of generic items at the retailers with emergency transshipment

As mentioned in the assumptions, although it may be possible to physically move generic items from retailer i to j, a build-up policy that would entice a certain retailer to hold more inventory than the other is not allowed. To summarize the operations in Figure 4.8a and Figure 4.8b, the retailer has three different possible alternatives in satisfying customer demand. These are a) from the generic inventory available at retailer i b) from the generic inventory available at retailer j and c) from replenishment from the central production facility during the current period. Otherwise, a great amount of backorder cost is incurred, calculated based on both quantity and backorder duration.

Cost Performance of the System

An important contribution to total cost is due to the management of generic items at the retailers. Since transshipment is allowed on a generic item basis, it is more likely that different item requests could be handled in respect to the System 2 dynamics defined previously. Accordingly, the costing of the system can be expressed in the following manner:

$$TC = h_0^0 \int_{t=0}^{T} OH_0^0(t)dt + \sum_{i=1}^{N} h_i^0 \int_{t=0}^{T} OH_i^0(t)dt + \sum_{k=0}^{M}\sum_{i=1}^{N} p_i^k \int_{t=0}^{T} B_i^k(t)dt + \sum_{t=0}^{T}\sum_{i=1}^{N} t_i T_{it} +$$

$$\sum_{t=0}^{T}\sum_{k=1}^{M}\sum_{i=1}^{N} f_i^k Y_t^k + \sum_{t=0}^{T}\sum_{i=0}^{N} A_i B_{it} + \sum_{t=0}^{T}\sum_{i=1}^{N}\sum_{j=1}^{N} c_{ij} X_{ijt}^0 \qquad \textbf{(28)}$$

4.8.5 Order of events in System 5

System 5 allows the processes to respond in both a make-to-stock and make-to-order manner, which was termed a hybrid strategy previously. If capacity or lead time constraints prohibit the system to work in a purely postponed state, a portion of capacity is reserved for regular make-to-stock operations, creating a capacitated or hybrid strategy. In such a system, some items are allowed to be postponed similar to System 3, whereas other items are manufactured similar to the system settings in System 1. The amount of generic items available at the central production facility to be converted to customized items was defined to be $Y_k(t)$. In this system, α fraction of the total generic items will be customized at the central production facility, denoted as $\alpha Y_k(t)$, whereas the rest is sent as generic items in the quantity of $(1-\alpha)Y_k(t)$, and customized at the retailers. The value of α determines the degree of postponement allowed in the system and if it is early postponement (customized at the central production facility) or late postponement (customized at the retailers). In our study alpha is assumed to be 0.25, implying that 25% of the raw materials are customized early at the central production facility, whereas 75% of the items are sent as generic inventory to the respective retailers and customized according to customer requests.

The central production facility and retailer's sequence of events maybe observed in Figure 4.9 and Figure 4.10a-b respectively. Figure 4.11 also shows the general implementation rules for both transshipment policies. Overall, transshipments allow the retailers to satisfy requests from the same echelon. The central production facility has a chance to produce and hold customized as well as generic items and it sends the retailers a bundle of these items. Thus, both generic as well as customized items are available at the retailers. The following sequence of events are distinctively possible through the hybrid strategy or System 5:

i. Customer requests to the retailers are shaped according to different item types. If customized items are available, then the retailer may satisfy customer requirements utilizing on-hand customized inventory. All requests may be satisfied in full, or partially backordered depending on the quantity available and the requested demand quantity.
ii. Else, if the retailer is facing demand of item k and excess generic item is available, the generic items maybe converted to customizable items as requested by the customer.

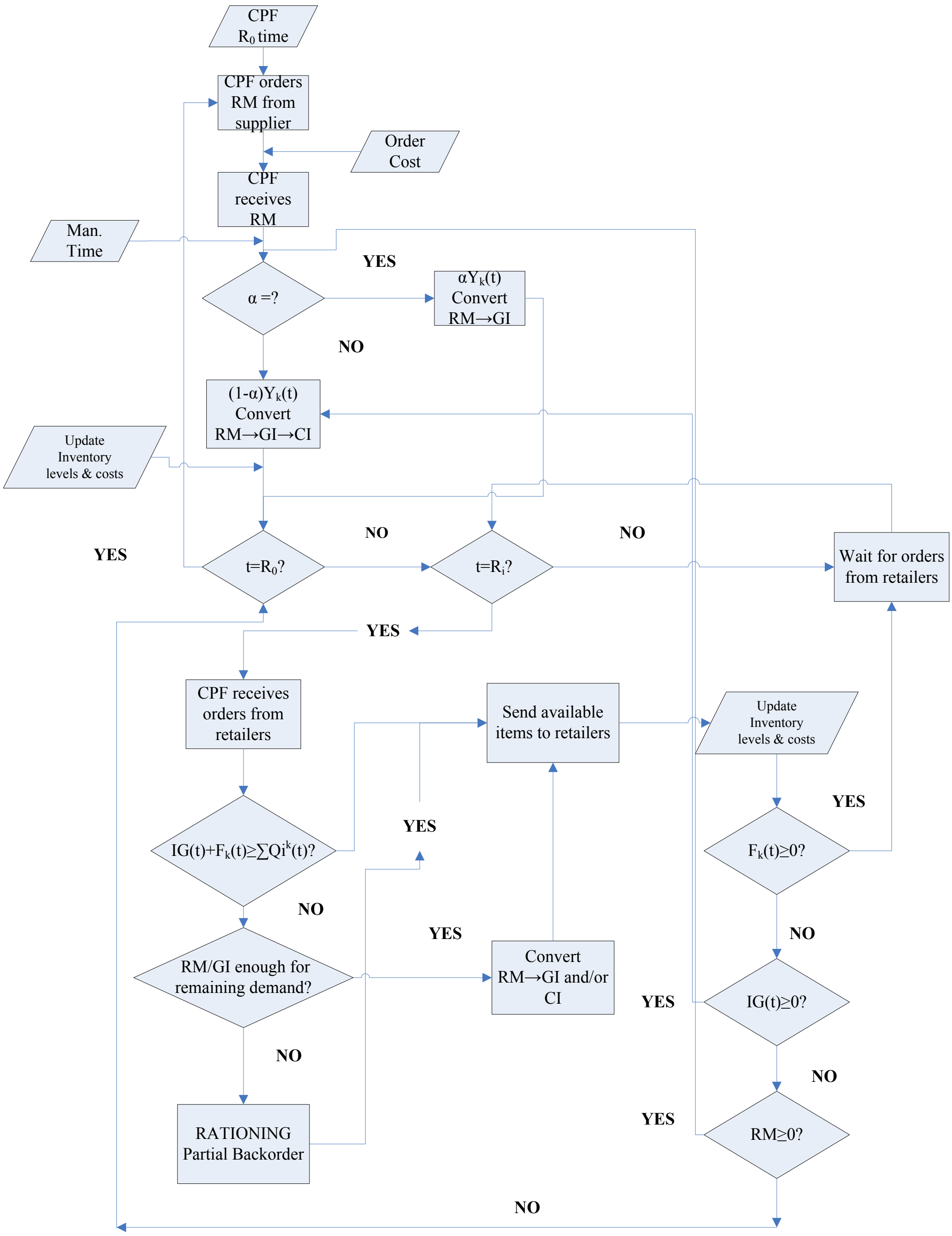

Figure 4.9 System 5: Flow of generic/customized items at the central production facility

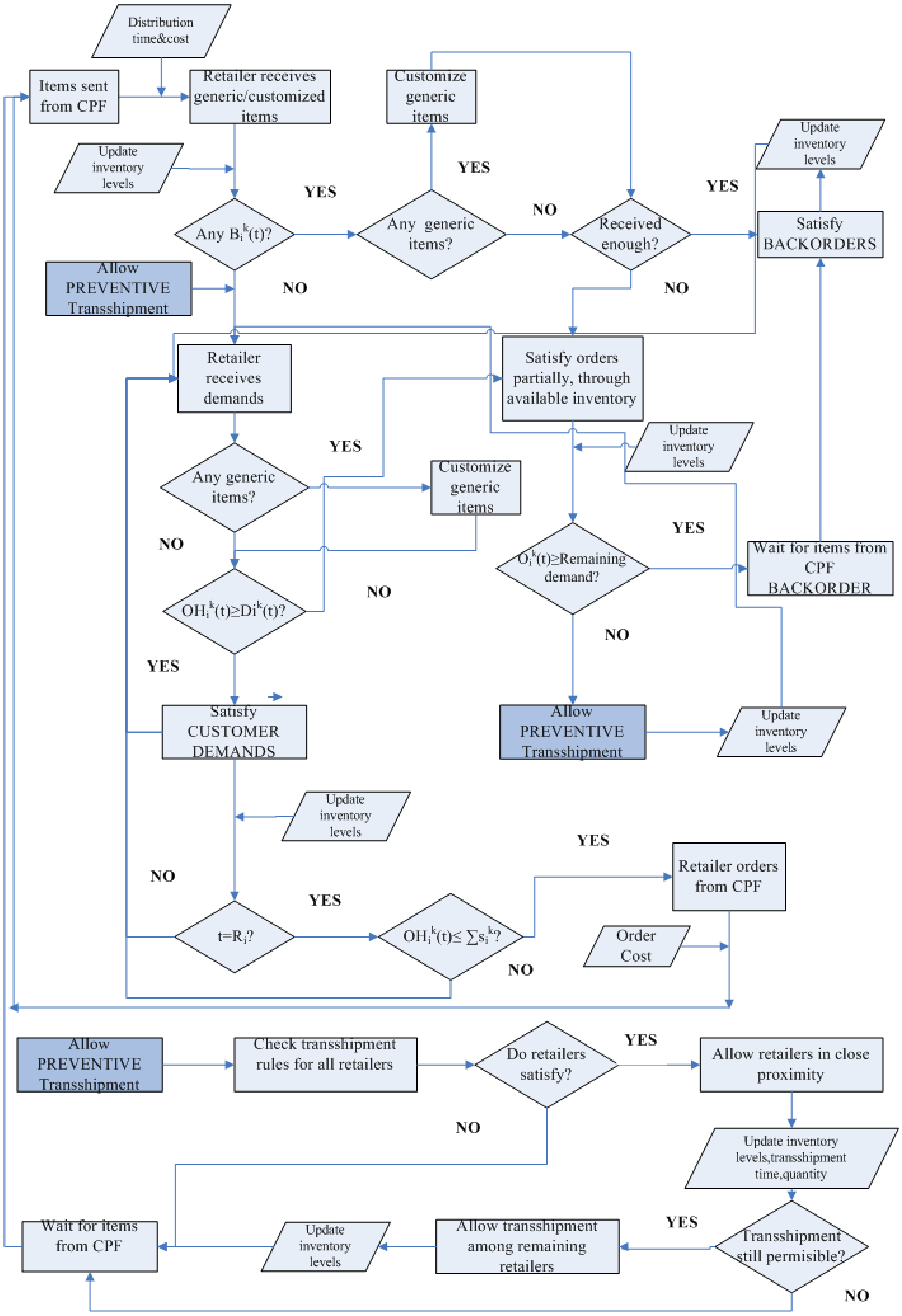

Figure 4.10a System 5: Flow of generic/customized items at the retailers with preventive transshipment

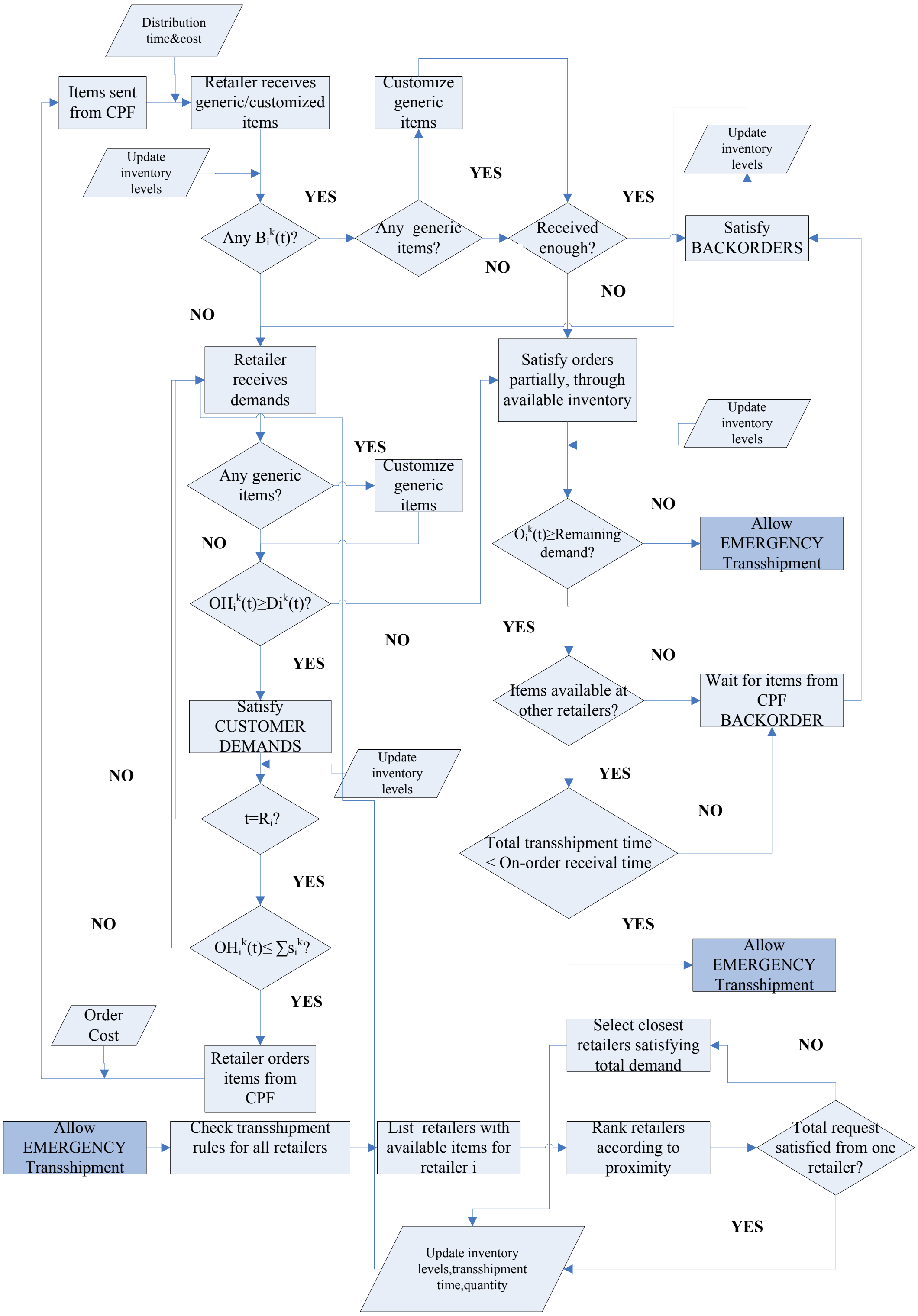

Figure 4.10b System 5: Flow of generic/customized items at the retailers with emergency transshipment

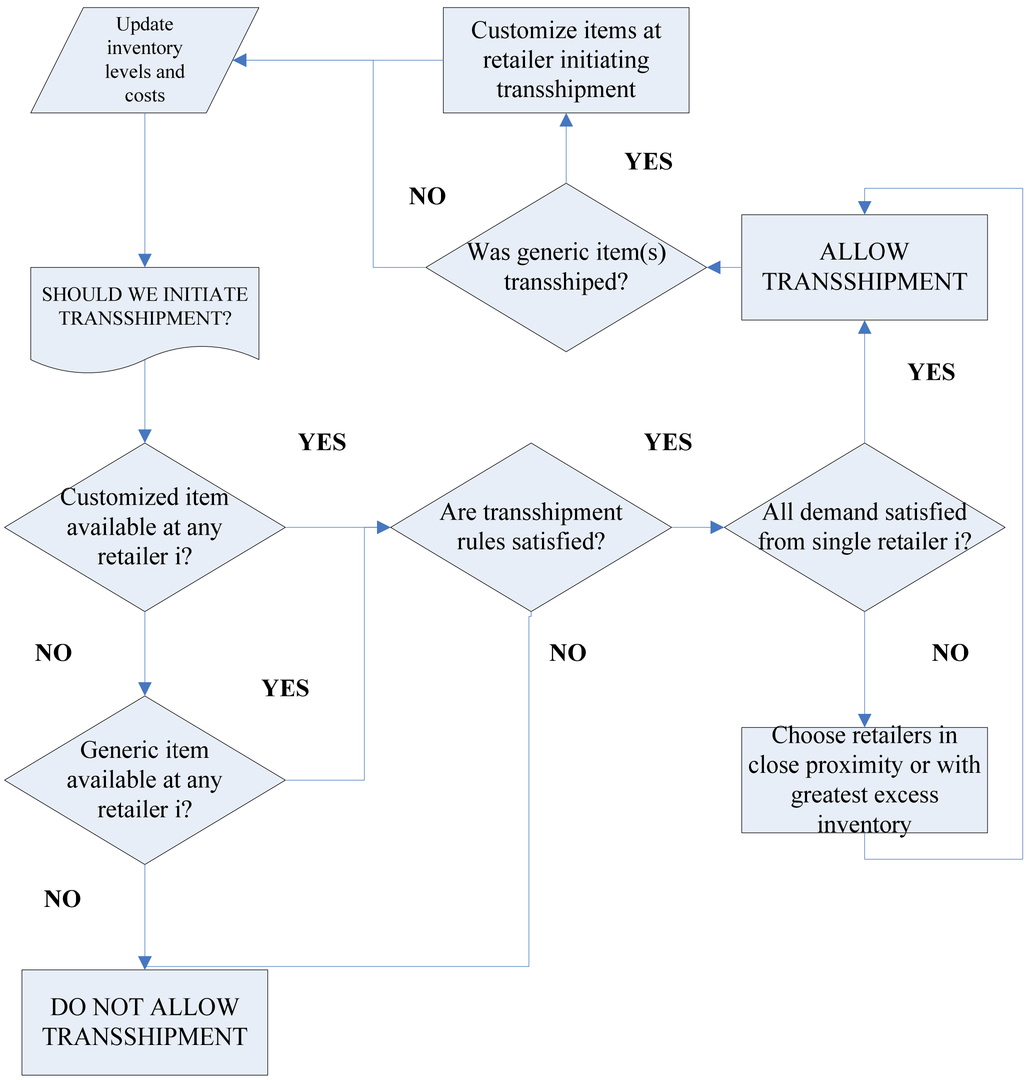

Figure 4.11 System 5: Main transshipment rules for both preventive/emergency transsshipment

iii. The system may resort to transshipment to provide for the item that is low in stock and being demanded from the customer before the replenishment interval using preventive transshipment or utilize emergency transsshipment to satisfy demand that is backordered. In transshipment implementations, priority is given to customized item k first at retailer j, if the item is not available at retailer i. Otherwise, generic items maybe requested from the neighboring retailer.

iv. If the amount of the customized item or generic item is not available at any of the other retailers, the retailers may check and accordingly request the generic/customized item from the central production facility. Items are replenished at the next review interval from the central production facility.

Cost Performance of the System

The performance of the system is greatly influenced by the amount of capacity allowed for postponement. If α=1, the hybrid system becomes System 2 where customized items are transshipped, and accordingly if α=0, the system reduces to the properties of System 4 where generic items are allowed to be transshiped. Unique to this system, customization maybe carried out either at the central production facility and/or retailers. Moreover, the type of inventories held at the retailers are not limited to either customized or generic items, where both are available to the customers. Total cost over time period [0, T] therefore becomes:

$$TC = \sum_{k=0}^{M} h_0^k \int_{t=0}^{T} OH_0^k(t)dt + \sum_{k=0}^{M}\sum_{i=1}^{N} h_i^k \int_{t=0}^{T} OH_i^k(t)dt + \sum_{k=0}^{M}\sum_{i=1}^{N} p_i^k \int_{t=0}^{T} B_i^k(t)dt +$$

$$\sum_{t=0}^{T}\sum_{i=1}^{N} t_i T_{it} + \sum_{t=0}^{T}\sum_{k=1}^{M}\sum_{i=0}^{N} f_i^k Y_t^k + \sum_{t=0}^{T}\sum_{i=0}^{N} A_i B_{it} + \sum_{t=0}^{T}\sum_{i=1}^{N}\sum_{j=1}^{N}\sum_{k=0}^{M} c_{ij} X_{ijt}^k \quad . \qquad \textbf{(29)}$$

CHAPTER 5

SYSTEM SIMULATION

In order to evaluate the five systems, simulation is used, because it is a tool that can best emulate the supply chain context and better model demand and supply uncertainties. In the study, the operational advantages of the five systems are compared by utilizing common input parameters and settings for the systems. ARENA 12.0 is used and the underlying coding language utilized is SIMAN. For each of the systems, source codes ranging from 30-250 pages are generated depending on the size and scope of operations. In order to describe and follow the operations in a comprehensive manner, high level modeling is used to create and represent the systems. The following steps are undertaken in order to represent the supply chain and problem context utilizing a simulation package:

a) Understanding the supply chain processes by identifying the logic behind the dynamics of the central production facility and the retailers through flowcharts. The inclusion of postponement strategies are investigated in literature and several sector examples are understood to create the systems. An important consideration within this scope is the timing of value creation. Customized items should be offered in a fast and reliable manner; otherwise the customer is not enticed to buy an item that has been created through postponement.
b) Creating the five model systems is important in order to understand the working principles of the systems, under various experimental settings. In various settings, although the customized end item and customer demand rates are the same, how the models react to similar settings is important in understanding the impact of these events within the supply chain.

c) Defining the operational context and increasing the credibility in the analysis is defined according to the guidelines from the work of Beamon (1998), Reiner (2005) and Olhager and Persson (2006). These are:

- **Production/Distribution Scheduling Dynamics:** Scheduling the receipt of raw material from the supplier, conversion of raw material to generic items at the central production facility and allowing customization at either the central production facility/ retailers.
- **Inventory dynamics:** The amount of safety stock, re-order and order-up-to levels are determined according to the customer demand function. The generic item, which is a potential make-to-stock item, has significantly longer manufacturing lead times than the customization process. Generic items maybe substituted for any customized item which is an important consideration in inventory management.
- **Number of echelons:** Two echelons are utilized in understanding multi-echelon dynamics in supply chains. The number of retailers within each echelon is varied for system comparison.
- **Customer Assignment/Fulfillment centers:** The central production facility is not allowed to fulfill the customer orders directly. It only has direct shipment to the retailers. Demand is satisfied solely by the retailers.
- **Retailer/Item Assignment and Item Differentiation:** The systems differentiate their scope of operations by allowing different forms of inventory to be held at the retailers. For example, System 5 allows generic/customized items to be held in both the central production facility and the retailers, whereas the other systems hold only generic or customized items at the central production facility and/or retailers. Accordingly, item differentiation is completed by giving the retailers the capacity to customize generic items in System 3,4 and 5, while System 1 and 2

are restricted to customization practices at the central production facility.

- **Number of items held:** In order to visualize the effects of postponement at least two different items are required. This is so that customized items can be derived from a generic item. In the system implementations, two, five and eight different item options are used.

5.1 Simulation Input

A terminating (finite-horizon) simulation is one that runs for some duration of time T_E, where E is a specified event (or set of events) which stops the simulation. Terminating simulation is used in the study, where the simulation opens at time '0' under specified initial conditions and closes at the stopping time T_E. Accordingly, in finite-horizon applications, the method of independent replications is to be included which aims to achieve independence across replications. There are several design parameters defined in the simulation system. The ones specific to all five system implementations are:

Planning time period: The planning time period is a day. All time related parameters are reflected in this unit. The simulations are run for 30 replications to ensure independence and to eliminate bias. The use of 30 replications also satisfies the central limit theorem which is important in the factorial analysis conducted.

Planning Horizon: The calculations are based on at most a two-week interval (250 hours).

Lead Time: The lead times in the system are supplier lead time, production/manufacturing lead time at the central production facility, distribution lead time, customization lead time at the the central production facility/retailers and transshipment lead times. These values are assumed to be deterministic.

Review period for central production facility: The central production facility reviews its raw material requests every R_0 intervals. An uncapacitated supplier has been chosen so that system dynamics is not affected by the external supplier.

Review periods for retailers: All the retailers have a common review interval of R_i which is either shorter or equal to the review interval for the central production facility.

Inventory control parameters: The order-up-to levels and safety stock levels for the retailers as well as the central production facility are calculated according to the principles defined in Chapter 4.

Cost parameters: Costing structure for the systems reflect realistic assumptions, with respect to the magnitude of cost items. Foremost, system implementations do not support backorders and thus are penalized with higher costs. Holding generic items are cheaper than holding customized items at either the central production facility and/or retailers. Other costs include customization and ordering costs both at the central production facility and at the retailers. If allowed in the system implementations, transshipment costs are also included.

Demand parameters: Customer demands are stochastic and is a function of item and retailer pairs. The coefficient of variation (CV) is taken as reference in evaluating retailer demand rates, where the mean is held constant and the standard deviation of demand is varied for different system implementations.

Transshipment and Rationing policies: If items are not available at the central production facility, it is rationed among the retailers. The rationing policy is defined in Chapter 4. Two different transshipment policies emergency and preventive are utilized in the different implementations.

5.2 Simulation Outputs

The basic performance measures are systemwide and customer service measures. Accordingly, these measures can be distinctively evaluated through:

a) **Customer service parameters:**

Average Fill Rate: The fraction of demand immediately filled from the stock on hand.

Average Percentage Backordered: Weighted average of all item demands not met on time at the retailers.

Average Order Lead Time: Lead time to satisfy customer demand from order receipt to the order delivery.

Average Number of Transshipments: Number and type of items transshipped among the retailers. It is used to evaluate the effectiveness of either transshipment policy: preventive or emergency.

b) **Supply chain performance:**

Average total cost of operations for different system implementations are defined in Chapter 4. Average total cost include on-hand inventory at the central production facility/retailers, backorder costs at the retailers and ordering costs at the central production facility/retailers. Also, distribution costs from the central production facility to the retailers, if allowed transshipment cost among the retailers and customization costs incurred either at the central production facility and/or retailers are also included.

The general working principle within the simulation implementation is summarized and can be viewed in Figure 5.1 respectively. The figure summarizes the input and output for different system implementations.

5.3 Simulation and System Model Construction

Five system models are created using three important sub-modules including the demand, central production facility and retailer sub-modules. Figure 5.1 describes the main inputs and outputs of the simulation module through the sub-modules. Brief descriptions about the functioning of these sub-modules are as follows:

Demand Sub-Module: Demand initiation is handled within this sub-module. Demands coming to the retailers are evaluated and questioned according to inventory positions at the retailers. If items are available at the retailer, orders are satisfied and deducted from on-hand inventory. The size of replenishment orders are updated according to current inventory levels and customer demands faced at the retailers.

Central Production Facility Sub-Module: The rationing policy and the distribution of items among the retailers are handled within this sub-module. Generic item conversion and customized item assignments are critical in this sub-module. An important function carried out by this sub-module is the distribution of items from the central production facility to the retailers. The assignment of transportation times to the respective retailers is also included within this sub-module. It is linked to the other sub-modules through the evaluation of on-hand and on-order inventory assignment variables and by centrally viewing the amount of demands currently faced at the retailers. Thus the production facility acts as a centralized authority in the supply chain having access to on-time demand information at the retailers.

Retailer Sub-Module: Retailer dynamics are defined within this sub-module construct. Initiation of transshipment policies and retailer orders to the central production facility are managed in this sub-module. The timing of order requests to the central production facility from the retailers, as well as the management of demand arrivals from the customers within the simulation event list are restructured and controlled within this sub-module. The distinctive features controlled by this sub-module include the review period that needs to be

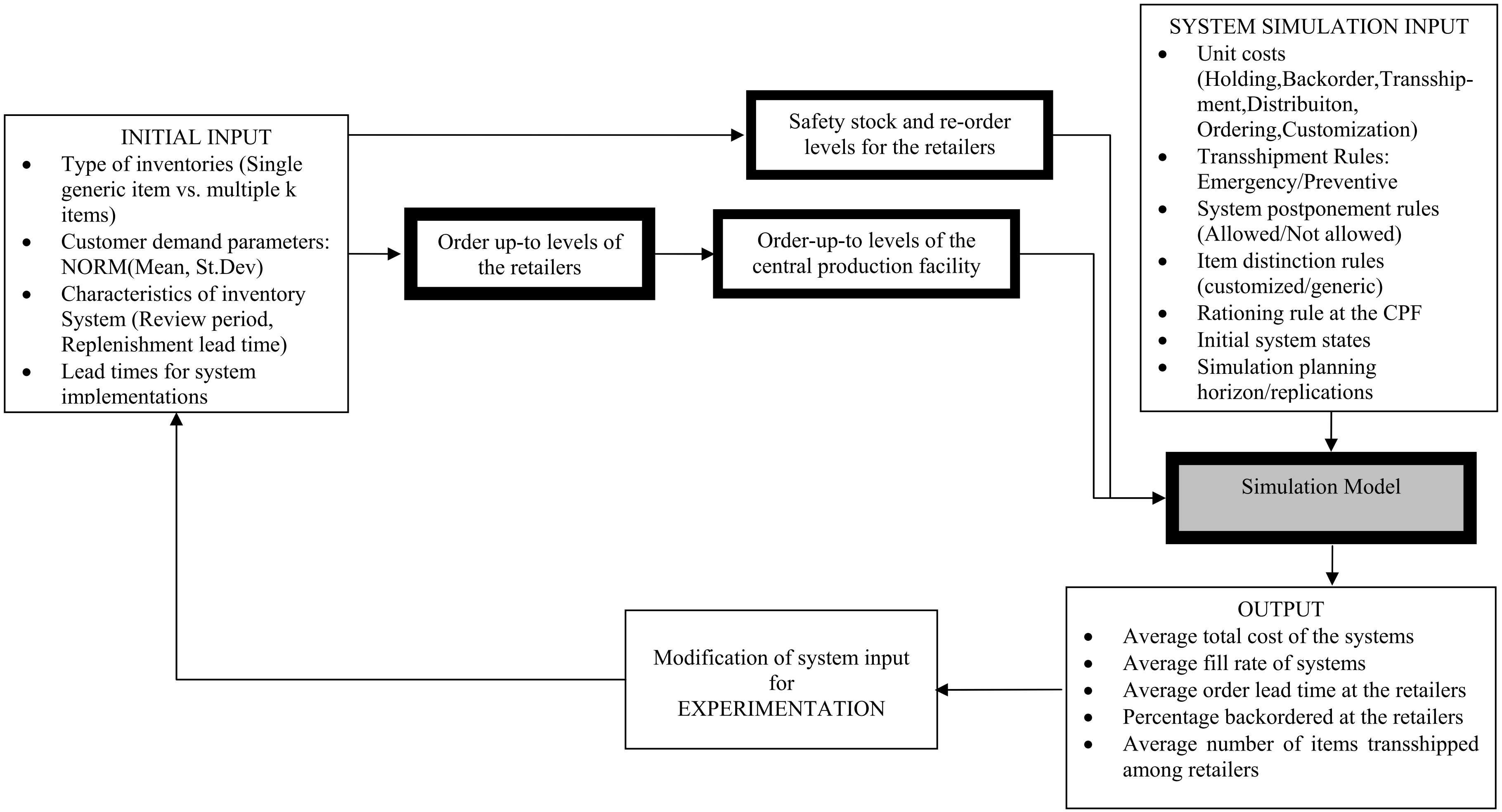

Figure 5.1 Working principle of the simulation models

monitored in simulation time, the re-ordering scheme and the amount of items to be ordered by the distinctive retailers, according to current inventory status and demand generated within the system. A global variable which is the order quantity is calculated and reflected in the retailer total inventory of items. Lastly, if transshipment is allowed in the system, this sub-module checks if transshipment is satisfied prior to a regular replenishment interval. If possible there is a transshipment cost that is incurred to the retailer initiating transshipment. All other costs are defined within the system module constructs within the simulation package.

5.4 Verification

In simulation studies, verification assures that the conceptual model is reflected accurately in the computerized representation. Banks *et.al.*(2000) defines verification as building the model right and assuring that the input parameters and logical structure of the model is correctly represented. As defined in the work by Law and Kelton (2000), eight steps maybe utilized to debug the computer program. These are listed as follows:

1) Writing and debugging the program in modules or subprograms instead of writing one big program.

Although five different systems are defined in our study, the three sub-modules are working in unision in all five system representations. Accordingly, for each of the system constructs, these three sub-modules were first created and individually evaluated if in fact they were working correctly. Individually, the functioning of the sub-modules is checked by observing the assignment of values to the defined local and global variables in the ARENA 12.0 program.

2) A structured walk-through of the program by more than one person to detect any problems in especially large programs.

Flowcharts and working principles are defined for all five systems in model construction. These flowcharts are given in Chapter 4 in evaluating system implementation. The sub-modules, previously defined are integrated and tested for conformance. If there is a problem in the definition of variables or logic operators, the ARENA 12.0 program gives an error and this is corrected on repeated occasions by sub-dividing the three sub-modules into smaller portions, to detect the position of error within the implementations due to the merging of these sub-modules. If the high-level constructs are not satisfactory in solving the problem at stake, the SIMAN code is observed and debugged through the RUN CONTROLLER, TRACE and DEBUG option in the ARENA program.

3) Utilization of different sets of input parameters and checking to see if the output changes as expected and creating extreme conditions such as congestion or starvation in the model.

In order to evaluate the importance of all five system implementations, extreme conditions and unique instances are created for all five systems and compared for several performance measures. This is to ensure that the systems are performing as intended and accordingly behaving similar to the expected outcomes of the implementation. For example, when the systems are starved and no raw material is available, there is a great increase in the amount of backordered items in the system. Similarly, if items are not available to the system at hand, transshipment is also not possible as expected, since a specific retailer is far from satisfying its own item demands. Thus, there is no motivation to send any item in anticipation (preventive transshipment) to item demands. Similarly, emergency transshipments are also not possible, because there is no item available to satisfy current demand quantities. The distinctions brought by the systems are also more evident in extreme conditions and in how the systems cope with certain extreme scenarios.

4) Tracing the model's operation to list contents of event lists and values of state variables.

The primary events affecting system dynamics are the initiation and arrival of raw material orders, magnitude of customer demands and timing of demand initiation which have a direct impact on variables such as on-hand and on-order inventory levels. Banks *et. al.* (2000) mentions the significance of two types of statistics: current contents and total count. Current contents refer to the 'spot' observation of state variables and how they change as events occur in the event list. Total count is the number of items that have entered a system at a given time frame. Within the model, defining and implementing item conversion is an important assesment in allocating resources to the retailers. Within a run, if a total of 240 raw material items are receieved and processed within the simulation time, it is imperative that the same amount is created for generic items. Likewise, for a system with two items, the sum of customized item production cannot exceed the generic items available. Thus, for four retailers with two distinctive item offerings at the retailer and with postponement, the system implements the following conversion and rationing among the items:
240 units of raw material items= 240 units of generic items= 46 units of generic items for Retailer 1 + 75 units of generic items for Retailer 2 + 56 units of generic items for Retailer 3 + 63 units of generic items for Retailer 4. The amount of total item A and item B conversion at the retailers is in fact, 106 units of item A + 134 units of item B respectively.

Other event instances such as the central production facility review time and retailer's review time are also checked. For example, for a simulation time of 250 hours, and an allowance of central production facility review of 1 week and retailer review of a day, the amount of review instances are checked. In this instance, the retailers are allowed 11 review instances, where the last review follow up is not allowed within the limited run time of the simulation. Similarly, the central production facility releases two order requests, but it cannot follow up retailer requests for the last week, because the simulation terminates in the middle of the week.

5) Running the model under simplifying assumptions and comparing with analytical results.

The systems are constructed hypothetically, thus there are no prior analytical results to compare. However, in order to test if the models are running as intended, they are run under several simplifying assumptions:

a) **Discrete demand instances:** Every retailer observes a fixed amount of demand items. For example, retailers face only 4 items every hour. At first, distinction is not made for item types; later this assumption is tested for different items. That is, if the total demand of the customer is 4 units, at first all the items requested are type A or type B, next the model is tested to see if the total demand coming to the retailer by a single customer is partitioned into two different unit item requests.

b) **Variation in transportation lead times:** The lead times for the systems are not distinguished according to retailer or item type. For example, all customization times for the items are assumed to be the same, moreover the time to distribute items to any of the retailers from the central production facility are also assumed to be the same in standard system implementations. However, these times are differentiated according to the magnitude of lead times, where it is reduced and increased incrementally with respect to the fixed lead time of four hours respectively.

c) **Transshipment lead times:** Transshipment lead times are critical in evaluating which retailers are prioritized in similar conditions. If the transshipment rules are satisfied for any of the retailers, selection or priority is given to the closest one among the retailers. This is critical in decreasing overall lead times. However, when all of the lead times are held the same, the selection of which retailer is to transship is observed within the event list. Priority is given to retailers listed first in the model constructs. It was often the case were the only decisive rule was the current inventory state at the retailer, which is important in satisfying transshipment conditions among the retailers. However, within this variation, there was no need for tie-breaking rules.

d) **Resources available:** The average order lead time of the generic material and the time it reaches the customer is an important consideration in fulfilling customer demands. The quantity of resources is increased to see if indeed the items coming in bulk are processed as intended. The system is also starved and system dynamics is observed. The arrival times of the resources from the supplier to the central production facility and then to the retailers are also observed. Timeliness of resource arrivals (raw material, generic items and customized items) is critical in satisfying customer orders on-time and avoiding backorders.

6) Utilizing animation to observe unexpected occurrences of events.

Animation is partially observed for critical events in the simulation event list. Especially, orders initiated by the central production facility/retailer or customer arrivals to the retailer, are two important instances that change system inventory dynamics. The backorder and on-hand holding costs are major cost items in the system, thus the state of the inventory variables are observed to evaluate if indeed the system is working in the state that it is intended. Figure 5.2 shows a sample run of 250 hours, observing the amount of on-hand generic items available at a specific retailer i within the simulation run time for System 1 implementation. The animation allows us to see, if there are serious deviations from system constructs.

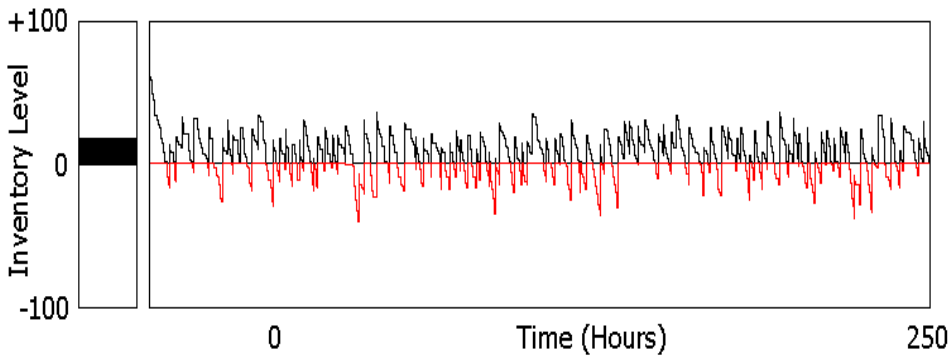

Figure 5.2 Sub-module demand management and operation analysis in System 1 at a retailer

7) Checking input distribution's parameters

The demands faced by the retailers for various items are assumed to be normally distributed with μ_{ik}, σ_{ik}^2 parameters. The interarrival times are assumed to be exponentially distributed, but several limiting instances have been created to check the demand generation at the retailers. Customers arriving at a retailer are not limited to a single item request. Thus, as the rate of customers increases, the amount of items requested within a day also increases. Input constructs have beeen manipulated such that a single customer is allowed per day, or at most a fixed amount is allowed, to see if the demands generated are evaluated and deducted from the current inventory status as necessary.

8) Utilization of a commercial simulation package to reduce the amount of programming required.

ARENA 12.0 is a high level simulation language allowing the representation of operations within any type of production or service context. The underlying code generated is SIMAN, however, model implementation and construction is not dependent on this low-level programming language. High level templates are utilized which brings ease in implementation and allows the use of animation within the system. Any bottlenecks or system disruptions are observed through these animation constructs.

5.5 Validation

Verification and validation are often carried out in unision. Validation compares the model and its behavior to the real system and its behavior. Since the systems are hypothetical, this step is done to reflect if the systems indeed create value if differentiation for the different systems are obserable, when run under different experimental settings. Naylor and Finger (1967) formulate a three-step approach for validation which is widely used in simulation and developed and outlined in Banks *et. al.* (2001).

a) Build a model that has high face validity by allowing potential users to be involved in model construction, checking for reasonability and correcting model deficiencies and checking credibility in simulation results. The systems are observed under different settings and the output results are accordingly evaluated. As seen in Table 5.1, the first sets of runs are instances describing the system states in different starvation states. The demand is assumed to be NORMAL (20,2). The review period for the retailers is 1 day, whereas for the central production facility it is one week. The ordering cost and customization costs are not included in order to observe the inventory states of the variables. From holding no safety stock, to allowing a fraction of total demand to be satisfied, the systems have acted to these responses accordingly. One of the striking observations is that in time of shortages, transshipments are not possible, as the retailers themselves can not satisfy their primal needs. Moreover, when utilizing postponement, in cases of starvation, the system performance improves, because the limited item inventory is allocated to the customer in the correct manner. In starvation, there are limited resources of item A and item B, but if the customer is requesting item B when in fact item A is available in stock, this also has a negative impact on total system performance, because it creates a mismatch in supply and demand and also because there is a no substitution principle enforced in the system. If the correct inventory is available the average total cost and average order lead times of the system decrease accordingly.

When comparing Table 5.1 outcomes and the nine distinctive scenarios, the working structure of the systems are detailed and the performance summarized through the primary performance measures available. Foremost, in the first two instances of starvation, the numbers of backordered items is quite high and the time to fill customer requests also constitutes a greater portion of simulation time. One of the problems in these settings is that the systems are starved and the systems do not tolerate any transshipment. In the third and fourth instances of the scenarios, the location of holding excess inventory is researched. Due to the timing of operations, the excess stock at the central production facility improves the overall backorder by a small amount and it is not very useful as it is not close to the point of consumption or the retailers. This supports the understanding that when non-negligible lead times are used, the stock available should critically be located close to the point of consumption, if a better performance is aimed. In Scenario 4, this structure is observed as the retailers have available stock which allows the systems to satisfy demand immediately. This is also reflected in the transshipment rates, in the sense that items are exchanged prior to facing stock-out at the retailers. Costs for various systems stem primarily from holding items in inventory prior to demand realization. System 3 utilizing postponement often results in good average total cost performance, however, increasing the customization time greatly hinders System 3 and System 4's performance. As mentioned in previous chapters, the timing of customization is a critical factor in system adoption. If it exceeds the timing of standard make-to-stock items, customers do not tolerate long lead time periods in the system. Increasing the transportation times also hinder the available stock that will cover the regular replenishment times and accordingly creates backorders in the system as reflected in Scenario 7. As the variance of item demands are altered in Scenario 8, the systems utilizing transshipment greatly increase the traffic that is apparent in such systems. There is greater need to satisfy increased demands through quicker strategies than regular replenishment. Lastly, the effect of review parameters greatly underlines the inflow of raw materials and its effect on system performance. As the raw materials in the central production facility are replenished more often, there is greater production capabilities which allow the creation of generic and/or customized items. Overall, the effect of postponement has been greatly observed as System 1 usually performs worst in most of the scenarios, whereas the pure postponement or hybrid strategies usually rank low in average total cost, but high in customer satisfaction which supports that the systems are working as intended under the assigned scenarios.

b) Validate model assumptions by identifying appropriate probability distributions. This assumes estimating parameters of hypothesized distributions and validating the assumed statistical model by a goodness of fit test. Since the systems constructed are hypothetical, the assumptions of lead time and demand parameters have been taken from previous study assumptions, as well as the

Table 5.1 Initial Simulation Results for Extreme Scenarios

SCENARIO 1: No safety stock; Available generic inventory 100 units	**Average Order Lead Time (min.)**	**Average % backordered**	**Average number of transshipments**	**Average Total Cost**
SYSTEM 1 Basic	100.46	99%	0	2038
SYSTEM 2 Transshipment	100.48	99%	2	2054
SYSTEM 3 Postponement	92.55	99%	0	1850
SYSTEM 4 Trans. + Postpon.	92.55	99%	0	1850
SYSTEM 5 Hybrid	89.15	98%	4	1803

SCENARIO 2: No Safety Stock; Available generic inventory 240 units	**Average Order Lead Time (min.)**	**Average % backordered**	**Average number of transshipments**	**Average Total Cost**
SYSTEM 1 Basic	94.74	93%	0	1726
SYSTEM 2 Transshipment	95.32	92%	15	1744
SYSTEM 3 Postponement	79.743	96%	0	1661
SYSTEM 4 Trans. + Postpon.	79.743	96%	0	1663
SYSTEM 5 Hybrid	78.15	90%	18	1267

SCENARIO 3: Safety Stock allocated at CPF: 100 item A, 100 item B	**Average Order Lead Time (min.)**	**Average % backordered**	**Average number of transshipments**	**Average Total Cost**
SYSTEM 1 Basic	93.62	92%	0	1904
SYSTEM 2 Transshipment	92.32	92%	34	1836
SYSTEM 3 Postponement	77.126	96%	0	1881
SYSTEM 4 Trans. + Postpon.	78.13	96%	0	1890
SYSTEM 5 Hybrid	77.96	90%	52	1545

Table 5.1 cont'd Initial Simulation Results for Extreme Scenarios

SCENARIO 4: Safety stock allocated to retailers for item A and B; 100 each	**Average Order Lead Time (min.)**	**Average % backordered**	**Average number of transshipments**	**Average Total Cost**
SYSTEM 1 Basic	92.12	92%	0	1735
SYSTEM 2 Transshipment	93.34	90%	42	1648
SYSTEM 3 Postponement	76.56	94%	0	1655
SYSTEM 4 Trans. + Postpon.	76.94	94%	5	1690
SYSTEM 5 Hybrid	75.96	88%	54	1598

SCENARIO 5: Parameter Variation: Stock at the retailers equal to the amount demanded	**Average Order Lead Time (min.)**	**Average % backordered**	**Average number of transshipments**	**Average Total Cost**
SYSTEM 1 Basic	0.001	0%	0	455
SYSTEM 2 Transshipment	0.042	1%	6	464
SYSTEM 3 Postponement	0.010	1%	0	286
SYSTEM 4 Trans. + Postpon.	0.052	2%	12	295
SYSTEM 5 Hybrid	0.049	1%	4	396

SCENARIO 6: Lead Time Variation: Customization time increased; regular system parameters	**Average Order Lead Time (min.)**	**Average % backordered**	**Average number of transshipments**	**Average Total Cost**
SYSTEM 1 Basic	0.008	2%	0	495
SYSTEM 2 Transshipment	0.056	4%	8	502
SYSTEM 3 Postponement	0.200	12%	0	485
SYSTEM 4 Trans. + Postpon.	0.290	10%	10	499
SYSTEM 5 Hybrid	0.120	5%	20	466

Table 5.1 cont'd Initial Simulation Results for Extreme Scenarios

SCENARIO 7: Lead Time Variation: Transportation time increased, regular system parameters.	**Average Order Lead Time (min.)**	**Average % backordered**	**Average number of transshipments**	**Average Total Cost**
SYSTEM 1 Basic	35.07	25%	0	795
SYSTEM 2 Transshipment	37.24	28%	14	702
SYSTEM 3 Postponement	34.35	29%	0	585
SYSTEM 4 Trans. + Postpon.	34.88	27%	26	603
SYSTEM 5 Hybrid	36.89	25%	44	599

SCENARIO 8: Parameter Variation: Increase of variance of item demands.	**Average Order Lead Time (min.)**	**Average % backordered**	**Average number of transshipments**	**Average Total Cost**
SYSTEM 1 Basic	0.203	8%	0	465
SYSTEM 2 Transshipment	0.56	6%	25	504
SYSTEM 3 Postponement	0.78	9%	0	345
SYSTEM 4 Trans. + Postpon.	0.84	8%	45	367
SYSTEM 5 Hybrid	0.79	7%	55	409

SCENARIO 9: Review Period Variation: Same review period for retailers and CPF.	**Average Order Lead Time (min.)**	**Average % backordered**	**Average number of transshipments**	**Average Total Cost**
SYSTEM 1 Basic	0.001	0%	0	378
SYSTEM 2 Transshipment	0.004	1%	10	396
SYSTEM 3 Postponement	0.1	2%	0	295
SYSTEM 4 Trans. + Postpon.	0.14	1%	8	285
SYSTEM 5 Hybrid	0.12	1%	14	305

system constructs common to all five systems. Limiting assumptions in supply chain models developed by earlier researchers are mentioned in the work of Venkateswaren and Son (2004) where common features include: aggregation of activities of a supply chain into a single delay variable (for example, the entire manufacturing process), absence of specific emphasis on transportation systems, infinite transportation and production capacities and available of timely and accurate information available at the right place and time.

c) Compare the model input-output transformations to corresponding input-output transformations of the real system.

Changes of single number parameters, such as arrival rate of customers, number of resources available, amount of safety stock available and the re-order levels are manipulated to view the system outputs. A critical observation is that the number of customers increases the load on the system, as customers request more than one item at a time. Repeated use of the model under the listed variations highlights the discrepancies among the backorder levels. The timing of customer arrivals and magnitude of item requests are critical in the assessment of our system. The interarrival times as well as the magnitude of demand arrivals are varied to observe the effect of these on overall system performance.

Minor changes of the form of statistical distribution, with respect to the mean and variance of the distributions are evaluated using different distribuitons including Poisson, Gamma and Normal distributions within model implementation. The effects of simplyfing assumptions in using such distributions are also evaluated with respect to the authors mentioned in Chapter 3.

Changes in the logical structure of a sub-system are created by including transshipment options for both customized and generic items. Similarly, in the hybrid system, the model parameters are created such that generic and customized items are recognized distinctively among the total inventory available in the system in order to differentiate item availability and handling both types of items within system implementation.

Major changes involving a different design for the new system are in fact constructed by implementing the five systems. Although, work in system validation requires a different system to be created purposefully for evaluating system constructs, the systems created are comparatively compatible for a detailed analysis. They are evaluated under common performance measures for proper system evaluation. In modeling the systems at hand, the level of complexity is held at a manageable level by working in abstract or high level modeling. The level of abstraction is influenced by several factors including data availability, expertise of the modeller, simulation software capabilities and time availability as summarized in Venkateswaran and Son (2004) and Hwarng *et. al.* (2005).

CHAPTER 6

EXPERIMENTAL DESIGN AND ANALYSIS

6.1 Experimental Factors

This chapter includes the results of the computational study and an assessment of the simulation results. A full factorial ANOVA experiment is conducted and possible levels of the experimental factors are computed by changing the relevant factor levels. ANOVA, a statistical technique is used to investigate and model the relationship between one or more independent variables and a response variable. The performance of the two-echelon system for different factors are observed through the main performance measures as: average total cost, output measures such as average number of transshipments, average order lead time (reflecting the time between order placement and its delivery), fill rate and percentage of items backordered in the system. The experimental design with the relevant factors, levels and descriptions are summarized in Table 6.1. Accordingly, (3*3*3*2*2*2) 216 experimental settings or scenarios are created. These experimental settings are tested for the five main systems defined in previous chapters. The simulation is run for 30 replications for each of the five systems, thus resulting in a total of (216*5*30) 32,400 simulation runs. Each simulation is run for 250 hours and each run begins with one cycle's inventory available at each retailer. System performance data is collected subsequent to a warm-up period in which steady-state conditions are achieved under all scenarios. We assume unlimited raw material supply, so that the performances of the policies are not obscured by supplier stockouts.

Table 6.1 Experimental Design Settings

Factor	Level	Level Description
Number of retailers	3	4, 6, 8
Number of items	3	2, 5, 8
Demand variation for items at each retailer	3	NORM(30,5),NORM(30,15),NORM(30,25) C.V. :Low,Medium,High
Review Periods of CPF/Retailer-Equal	2	CPF 1 day ; Retailers 1 day, CPF 5 days ; Retailers 5 days
Review Periods of CPF /Retailer -Unequal	2	CPF 2 days ; Retailers 1 day, CPF 5 days ; Retailers 1 day
Transshipment Policy	2	Preventive, Emergency

Choice of experimental factors and initial conditions

The experimental factors chosen are selected in order to capture the relevance of postponement among the five systems defined. One of the main factors in the adoption of postponement is to mitigate the risks of demand variation reflected through different item alternatives and the frequency of these alternatives as a function of the coefficient of variation. System policies regarding the functioning of the supply chain is reflected through the number of retailers, review intervals, choice of adoption of a transhipment policy and postponement strategy. In order to interpret the effect of these factors, some input parameters with regard to the costing structure and lead times are kept unchanged during the experimentation. Demand for the item at each retailer is stationary and stochastic, while delivery lead times are held deterministic for the sake of better comparison. Backordering is allowed assuming a FIFO principle within the systems. System parameters are summarized in Table 6.2.

Assumptions in the derivation of these parameters are as follows:

a) Satisfying customer demand at the instance of request is an important evaluation criterion reflected using the fill rate. The system allows all orders to be backordered; however, it strictly penalize shortages which are detrimental to customer satisfaction, thus resulting in higher cost.
b) Customer requests are satisfied at the retailers, thus backorder costs are incurred at the lower echelon.
c) Holding cost for customized items at the central production facility or at the retailer is higher than the holding cost for generic items in either location. However, assuming that the central production facility produces in large volumes, the per unit holding cost at the central production facility is smaller than that of any of the retailer locations.
d) Transshipment is more costly than the distribution of items, because it is an extra oppurtunity to satisfy the request in a shorter period, thus foregoeing longer backorder costs.
e) Transshipment time among any of the retailers in an echelon is a factor of proximity. For example, if there are eight retailers, it is assumed that retailer 1 and retailer 8 are the farthest, taking approximately 3.5 hours to satisfy a request between these two retailers.
f) Customization is allowed at the retailers if postponement is allowed within the system configurations. Since, the central production facility is assumed to work in bulk, the per unit customization cost is cheaper at the lower echelon. Customizing an item is also shorter than converting an item into a generic form.
g) Fixed ordering costs are incurred at the central production facility and the retailers. It is an important contributor to overall average total costs in system implementations.
h) The interarrival times of the customers are held stochastic using an exponential time function. However, due to the demand function, the quantity of items requested may change accordingly.

Table 6.2 Basic System Parameters

Cost items	
Distribution costs from CPF to retailers	3 units/item-lot
Transshipment costs among retailers	4 units/item
Customization cost at the retailers	0,75 units/item
Customization cost at the CPF for customized item	0,5units/item
Holding cost at the CPF for generic items	1,5 units/ item-time
Holding cost at the CPF for customized items	2 units/ item-time
Holding cost at the retailers for generic items	2,25 units/item-time
Holding cost at the retailers for customized items	2,75 units/ item-time
Backorder cost incurred at the retailers	5 units/ item-time
Fixed ordering cost at retailers/CPF	10 units/order
Transportation Lead Times	
Supplier to CPF replenishment time	5 hours
Transshipment time among retailers	30 minutes-3.5 hours
Distribution lead time from the CPF to the retailers	3 hours
Production Lead Times	
CPF Generic Conversion (Raw material (RM) to Generic item (GI))	4 hours/10 item-lot
Customization time at CPF/Retailers	5 minutes/item
Interarrival time of customer requests	
Customer demand arrival rate at a retailer	Exponential (1) hours

6.2 Experimental Analysis

For the 216 experimental settings, simply listing the results are not meaningful in the analysis of these systems. To understand the root cause of a performance measure, the significance of the individual as well as the interaction of key factors are evaluated and criticized in the assessment of the systems. A full factorial experimentation has been defined and evaluated through MINITAB 15.0 statistical software. The summary results of the statistical analysis of the output data obtained from the 32,400 simulation runs are shown in Tables 6.3 and Table 6.4. Foremost, Table 6.3 summarizes the results of the full factorial ANOVA experimentation and indicates the significance level at which there are no differences in system performance, with respect to the various criteria, due to the main and second order interactions of the five factors considered in the experimentation.

Table 6.3 Full Factorial ANOVA Significance Results

	Average Order Lead Time (minutes)					Average Fill Rate					Average % Backordered				
	SYSTEMS					SYSTEMS					SYSTEMS				
EFFECT	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**
NOR	<0.001	0.012	<0.001	<0.001	0.001	<0.001	<0.001	<0.001	0.006	0.087	0.001	0.012	0.049	0.233	<0.001
NOP	0.004	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.017	0.836	<0.001	<0.001	<0.001	<0.001	<0.001
DV	0.067	0.21	0.152	0.241	0.032	<0.001	<0.001	0.256	0.106	0.003	0.012	0.141	0.023	0.069	0.009
RP	<0.001	<0.001	0.004	0.001	0.001	0.234	0.504	<0.001	0.004	0.021	0.246	<0.001	0.003	0.001	0.037
TP	0.366	0.007	0.995	0.141	0.027	0.452	0.341	0.243	0.177	0.151	0.199	0.352	0.045	0.126	0.096
NOR*NOP	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.009	<0.001	<0.001	<0.001	<0.001	<0.001
NOR*DV	0.583	0.244	0.035	0.015	0.334	0.425	0.437	0.016	0.003	0.127	0.762	0.485	0.60	0.817	0.008
NOR*RP	0.019	0.311	0.058	0.075	0.613	0.608	0.357	0.017	0.014	0.058	0.448	0.514	0.938	0.986	0.986
NOR*TP	0.828	0.996	0.941	0.745	0.526	0.987	0.827	0.537	0.558	0.424	0.874	0.747	0.460	0.295	0.391
NOP*DV	0.646	0.759	0.881	0.954	0.458	0.023	0.509	0.803	0.405	0.361	0.180	0.723	0.987	0.538	0.023
NOP*RP	0.137	0.314	0.040	0.180	0.017	0.720	0.469	0.054	0.012	0.031	0.703	0.453	0.073	0.021	0.981
NOP*TP	0.984	0.970	0.999	0.682	0.738	0.930	0.885	0.896	0.817	0.920	0.989	0.758	0.990	0.305	0.649
DV*RP	0.475	0.666	0.633	0.380	0.398	0.054	0.009	0.303	0.012	0.386	0.042	<0.001	<0.001	<0.001	0.314
DV*TP	0.638	0.001	0.738	0.346	0.196	0.053	0.069	0.030	0.034	0.351	0.191	0.024	<0.001	0.001	0.030
RP*TP	0.447	0.165	0.687	0.152	0.988	0.997	0.777	0.844	0.894	0.967	0.988	0.020	0.809	0.910	0.189

KEY:

NOR: Number of Retailers **NOP:**Number of Products **DV:** Demand Variation **RP:** Review Periods

TP: Transshipment Policy **NA:** Not Applicable

Table 6.3 cont'd Full Factorial ANOVA Significance Results

	Average Number of Transshipments					**Average Total Cost**				
	SYSTEMS					**SYSTEMS**				
EFFECT	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**
NOR	NA	0.001	NA	0.122	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
NOP	NA	0.084	NA	0.983	0.282	<0.001	<0.001	<0.001	<0.001	<0.001
DV	NA	<0.001	NA	0.017	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
RP	NA	<0.001	NA	<0.001	<0.001	0.106	0.285	<0.001	<0.001	<0.001
TP	NA	0.652	NA	0.001	0.136	0.17	0.668	0.05	0.945	0.47
NOR*NOP	NA	0.004	NA	0.537	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
NOR*DV	NA	0.080	NA	0.817	0.247	0.613	0.655	0.845	0.981	0.383
NOR*RP	NA	0.107	NA	0.955	0.095	0.823	0.830	0.823	0.879	0.752
NOR*TP	NA	0.501	NA	0.220	0.589	0.958	0.928	0.796	0.539	0.690
NOP*DV	NA	0.965	NA	0.230	0.899	0.973	0.981	0.242	0.049	0.429
NOP*RP	NA	0.985	NA	0.990	0.424	0.998	0.989	0.757	0.629	0.747
NOP*TP	NA	0.893	NA	0.197	0.746	0.819	0.681	0.878	0.472	0.677
DV*RP	NA	0.001	NA	<0.001	0.249	0.902	0.981	0.795	0.893	0.919
DV*TP	NA	0.870	NA	0.854	0.638	0.202	0.941	0.042	0.467	0.225
RP*TP	NA	0.053	NA	0.280	0.190	0.993	0.998	0.921	0.967	0.998

Table 6.4 Average System Performance Measures for each factor level and results of multiple pairwise Tukey's groupings

FACTORS	LEVELS	Average Order Lead Time (Minutes)					Average Fill Rate					Average % Backordered				
		SYSTEMS					SYSTEMS					SYSTEMS				
		1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
NOR	4	10,27 {2}	10,15 {1}	11,73 {2}	11,84 {2}	11,99 {2}	94,92 {3}	94,25 {2}	95,36 {2}	95,20 {2}	95,24 {1}	12,58 {1}	12,92 {1}	9,26 {2}	8,65 {1}	7,26 {1}
	6	9,10 {1}	9,57 {1}	10,95 {1}	11,24 {2}	11,05 {1}	92,86 {2}	92,95 {2}	96,49 {2}	95,75 {2}	94,21 {1}	13,69 {1}	13,48 {1}	8,14 {1}	8,44 {1}	9,98 {2}
	8	9,26 {1}	9,56 {1}	10,47 {1}	10,54 {1}	11,02 {1}	90,39 {1}	90,07 {1}	94,16 {1}	94,09 {1}	92,75 {1}	15,69 {2}	15,49 {2}	9,90 {2}	9,57 {2}	10,03 {2}
NOP	2	9,01 {1}	9,27 {1}	10,17 {1}	10,43 {1}	10,59 {1}	95,25 {2}	94,22 {3}	96,65 {2}	95,79 {2}	94,26 {1}	10,92 {1}	11,77 {1}	7,19 {1}	7,19 {1}	7,39 {1}
	5	9,58 {1}	9,74 {1}	10,95 {1}	10,97 {1}	11,20 {2}	91,61 {1}	92,01 {2}	94,46 {1}	94,29 {1}	93,90 {1}	13,96 {2}	13,54 {2}	9,44 {2}	9,23 {2}	9,23 {2}
	8	10,08 {2}	10,43 {2}	12,03 {2}	12,07 {2}	12,27 {2}	91,24 {1}	90,65 {1}	94,88 {1}	94,94 {1}	94,07 {1}	17,14 {3}	16,62 {3}	10,77 {3}	10,31 {2}	10,61 {3}
DOV	Low	9,50 {1}	9,60 {1}	10,87 {1}	10,90 {1}	10,94 {1}	90,96 {1}	90,54 {1}	95,25 {2}	94,59 {1}	94,58 {3}	13,58 {1}	14,06 {2}	8,69 {1}	8,84 {1}	8,73 {1}
	Medium	9,92 {1}	10,09 {2}	11,36 {2}	11,40 {2}	11,65 {2}	94,53 {3}	94,18 {3}	95,75 {2}	95,59 {2}	94,49 {2}	13,30 {1}	13,15 {1}	8,61 {1}	8,25 {1}	8,48 {1}
	High	9,20 {1}	9,74 {1}	10,85 {1}	11,18 {2}	11,54 {2}	92,53 {2}	92,54 {2}	94,81 {1}	94,77 {1}	92,55 {1}	15,75 {2}	15,08 {3}	10,55 {2}	9,97 {2}	10,66 {2}
RP (CPF/Retailer) EQUAL	1 day\1day	8,04 {1}	8,86 {1}	10,99 {2}	11,47 {2}	11,77 {2}	93,05 {2}	92,42 {2}	95,90 {3}	95,24 {2}	94,23 {1}	14,66 {2}	14,75 {2}	8,33 {1}	8,03 {1}	8,24 {1}
	5 days\ 5 days	11,10 {4}	11,05 {3}	11,73 {3}	11,75 {2}	11,88 {2}	91,50 {1}	91,57 {1}	93,60 {1}	93,64 {1}	95,75 {2}	14,62 {2}	16,20 {3}	11,06 {2}	10,97 {2}	10,48 {2}
RP (CPF/Retailer) UNEQUAL	2 days\1day	9,47 {2}	9,62 {2}	9,62 {1}	10,44 {1}	10,71 {1}	93,12 {2}	92,82 {2}	96,20 {3}	95,65 {2}	94,85 {1}	13,37 {1}	12,17 {1}	8,40 {1}	8,17 {1}	9,02 {1}
	5 days\ 1day	10,05 {3}	9,95 {2}	11,06 {2}	10,94 {1}	10,97 {1}	93,03 {2}	92,79 {2}	95,52 {2}	95,47 {2}	94,41 {1}	13,17 {1}	12,60 {1}	8,77 {1}	8,53 {1}	8,80 {1}
TP	Preventive	9,68 {1}	10,11 {2}	11,05 {1}	11,32 {1}	11,59 {2}	92,48 {1}	92,13 {1}	95,11 {1}	94,76 {1}	93,76 {1}	14,37 {2}	13,66 {1}	9,62 {2}	9,26 {2}	9,05 {2}
	Emergency	9,46 {1}	9,44 {1}	11,05 {1}	10,93 {1}	11,03 {1}	92,98 {1}	92,75 {1}	95,64 {1}	95,35 {1}	94,48 {2}	13,49 {1}	14,37 {2}	8,41 {1}	8,38 {1}	8,54 {1}

Table 6.4 cont'd Average System Performance Measures for each factor level and results of multiple pairwise Tukey's groupings

FACTORS	LEVELS	Average Number of Transshipments					Average Total Cost				
		SYSTEMS					SYSTEMS				
		1	2	3	4	5	1	2	3	4	5
	4	NA	17,07	NA	24,77	15,55	1329,17	1362,06	1120,04	1250,14	1257,27
			{1}		{2}	{1}	{1}	{1}	{1}	{1}	{1}
NOR	6	NA	25,20	NA	8,44	19,34	1628,32	1695,67	1416,38	1460,89	1486,15
			{2}		{1}	{1}	{1}	{2}	{2}	{2}	{2}
	8	NA	25,92	NA	27,10	26,74	1921,04	1987,02	1624,01	1780,55	1734,53
			{2}		{2}	{2}	{2}	{3}	{3}	{3}	{3}
NOP	2	NA	20,22	NA	24,22	18,74	1189,96	1241,54	1168,96	1225,92	1180,41
			{1}		{2}	{1}	{1}	{1}	{1}	{1}	{1}
	5	NA	21,93	NA	24,52	21,33	1637,74	1679,22	1321,35	1481,74	1421,09
			{1}		{2}	{2}	{2}	{2}	{1}	{1}	{2}
	8	NA	26,04	NA	10,31	21,63	2050,91	2124,08	1524,62	1783,09	1742,38
			{2}		{1}	{2}	{3}	{3}	{2}	{2}	{3}
DOV	Low	NA	16,19	NA	21,36	18,34	1538,37	1580,26	1308,20	1401,28	1355,72
			{1}		{1}	{1}	{1}	{1}	{1}	{1}	{1}
	Medium	NA	22,62	NA	28,31	17,62	1628,23	1679,35	1473,11	1507,69	1457,31
			{2}		{3}	{1}	{2}	{2}	{2}	{2}	{2}
	High	NA	33,37	NA	23,42	28,75	1735,39	1819,28	1402,51	1505,87	1554,12
			{3}		{2}	{2}	{3}	{3}	{2}	{2}	{3}
RP (CPF/Retailer) EQUAL	1 day\ 1day	NA	29,92	NA	31,33	28,11	1748,16	1819,33	1540,13	1588,84	1537,67
			{4}		{3}	{4}	{2}	{2}	{2}	{2}	{2}
	5 days\ 5days	NA	12,62	NA	13,73	13,31	1356,46	1406,55	1191,40	1229,77	1195,20
			{1}		{1}	{1}	{1}	{1}	{1}	{1}	{1}
RP (CPF/Retailer) UNEQUAL	2 days\ 1day	NA	26,57	NA	26,20	22,44	1753,33	1809,04	1589,81	1646,96	1584,44
			{3}		{2}	{3}	{2}	{2}	{2}	{3}	{2}
	5 days\ 1day	NA	20,37	NA	25,37	16,82	1780,36	1821,87	1633,25	1662,86	1616,11
			{2}		{2}	{2}	{2}	{2}	{3}	{3}	{2}
TP	Preventive	NA	23,16	NA	21,25	21,60	1642,91	1782,90	1469,35	1589,72	1450,02
			{2}		{1}	{2}	{1}	{2}	{1}	{2}	{1}
	Emergency	NA	22,61	NA	28,82	19,14	1588,31	1664,27	1416,76	1491,60	1430,50
			{1}		{2}	{1}	{1}	{1}	{1}	{1}	{1}

Only a few of the higher order interactions exhibit any meaningful difference, thus only those that are meaningul are reported. Table 6.4 shows the means of the performance measure values for each of the factor levels considered in the study. This table also reflects the pairwise posteriori comparisons between the factor levels, using Tukey's procedure. Tukey's procedure investigates the significance of all possible differences between the populations means listed for the different factor levels (Baneerjee *et. al.,* 2003). A pairwise t or z test is not meaningful for our assessment, because utilizing such a technique would lead to misjudgement as each pair of observation would create more Type I error in the evaluation. Tukey's test is carried out for all five system implementations in order to discern the distinction of the systems defined in our study. The groupings in Table 6.4 contained in curly brackets indicate no significant difference amongst factor levels within any group, while between-group differences are statistically significant at 0.01 level, which is the Tukey's family error rate that is tolerable in our assessment. The significance level is usually a choice between 5% and 1%. The significance level reflects the likelihood of Type I error in the experimental design, thus selecting a smaller significance level implies higher likelihood of correct assessment. The factor levels indicated in curly brackets are then ranked in ascending order of magnitude with respect to each of the performance measures defined in the study.

6.2.1 Evaluation of the main factor levels

The primary effects for each of the factor levels are important in distinguishing the significance of these factors on the performance measures. Accordingly, an assessment of main factor levels is detailed in this section.

6.2.1.1 Number of retailers

The number of retailers is significant for most of the performance measures defined in the system. Overall, increasing the number of retailers tends to significantly decrease service level measures, but increases transshipment oppurtunities. Several observations follow with regard to the performance measures:

Average Order Lead Time: Among the levels of retailers, the systems are often indifferent in utilizing six or eight retailers such that they fall in the same Tukey's groupings. An interesting observation is that average customer order lead time increases as the number of retailers is decreased. For example, utilizing eight retailers helps overall average order lead time. This could be attributed to the transshipment policies implemented as it could create more oppurtunities to fullfill customer requests among any of the possible retailers. The worse case instances for the order lead times are observed in System 4 and System 5 implementations, which would suggest that utilizing a preventive transshipment policy for generic items may adversely affect system performance as overall inventory imbalance is more likely to be affected.

Average Fill Rate: The number of retailers is very critical in overall fill rate performance. As the number of retailers increases the fill rate performance duely degrades among the systems. As postponement practices are allowed in Systems 3-5, utilizing four or six retailers become less meaningful. The number of product/item combinations and average inventory held in the previously mentioned systems results in similar average fill rates. Increasing the number of retailers to eight, accordingly does not improve the average fill rates.

Average % Backordered: Consistent with the conventional wisdom, the average % of backordered items increases as a function of the number of retailers. Finding the correct item at a specific retailer becomes harder as the number of retailers as well as the product/item offerings increase. Postponement duely helps the number of backordered items to decrease, as items have not been comitted to specific finalized items. There is more than 35% improvement in overall average percentage of backorders as the retailers adopt postponement strategies in Systems 3 to 5.

Average Number of Transshipments: As the number of retailers increases, so does the oppurtunity to satisfy customer requests within the supply chain. The customer has more choices in the selection of retailers to satisfy its demand, but maybe least likely to fulfill a request at a particular retailer due to different stock levels of different items. Thus, there maybe enough inventories within the supply chain, however, the required amount and specific type of inventory may not be available at a particular retailer. This provides oppurtunities for the retailers to satisfy customer requests through more transshipments and accordingly availing the imbalance in the supply chain structure. Therefore, as the number of retailers increases, so does the amount of items exchanged.

Average Total Cost: Pooling the risk of inventory is deteriorated as the number of retailers increase. Since the items are not centralized, overall system cost due to holding and backorder costs incurred at the different retailers significantly affect system performance. The distribution costs are similar, as the amount of total items distributed within the supply chain is the same within all five system implementations. Overall, there is at least 25% increase in total cost, as the supply chain structure increases from four retailers to eight retailers. The fixed ordering cost is an important contributor to overall supply chain costs. It may account for as much as 30% of overall system costs and may duely increase/decrease as the order cost per retailers and central production facility is changed, which is important in total cost evaluation. The costs are evenly distributed in the four retailer setting where all five system implementations have similar costs.

6.2.1.2 Number of products/items

The number of item offerings also seems to show statistically significant results. The variety of items offered is a function of the plethora of customer requests in the current era. However, as more products/items are offered, the risk of obsolescence also vastly increases due to the mismatch of customer requests and availability of the items. We observe the following with regard to the performance measures:

Average Order Lead Time: The systems are often indifferent between offering two items instead of five items. However, as the number of items increases, the average order lead time also increases within the systems. Overall, this marginal difference is as much as 15 %, detrimental to the customer service level of order lead time, as the number of items offered increase from two to five, or five to eight.

Average Fill Rate: When customized items are held in retailer inventory, as seen in System 1 and System 2 implementations, the overall fill rates are distinctively different for the different numbers of item offerings. Postponement activities in Systems 3 and 4 create a more impartial fill rate attainment, as well as an increase in the overall average fill rate. Interestingly enough in System 5, offering either five or eight items makes the system indifferent in fill rate attainment. This can be attributed to the 'partial' capacity of the retailers to hold both customized and generic items. The benefits of holding generic items are duely reflected in this measure.

Average % Backordered: The numbers of items offered do not give statistically significant results for all systems except System 5. Overall, the system with two items has a lower backorder level which is meaningful enough as it is easier to find two items rather than eight items within the supply chain implementation.

Average Number of Transhippments: The amount of items transhipped increases as the number of generic items available in the system increase. Five and eight item offerings are often in the same Tukey grouping, emphasizing the importance of generic items. Customized items are often requested in emergency transshipments, rather than emergency transshipments for all system implementations..

Average Total Cost: Backorders are sensitive to the variety of items offered, as well as the total demand for the items. Accordingly, the average total cost is different for each item offering and respective system. In the system implementations, the amount of items offered is matched with the available generic inventory, making item offerings for two or five indifferent among system evaluations for Systems 3 and 4. Product/item offerings are more costly than the effect of the number of retailers. As the number of items is increased from two to five, this causes an increase of 17% on overall aveage total system costs. As the item offerings is increased from five to eight the increase becomes as much as 30%. Although in either change three items are added the overall item offerings, the effect on cost after five items is much more than an increment from two products.

6.2.1.3 Demand Variation

Demand variation is found to be insignificant for the order lead time performance measure. The availability of the specific item and its quantity is important, however since an item request is not backordered for the whole request, this maybe duely reflected in the results. System performance is adversely affected in terms of backorder measures, as well as the number of lateral transhipments in some system implementations. Higher uncertainty in demand tends to result in lower customer service at the retailers and more transshipment.

Average Order Lead Time: Medium and high demand variation have the same Tukey groupings. The five system implementations have similar groupings, where order lead time is fourand to be indifferent to different system implementations. This is also supported by the significance level given in Table 6.3.

Average Fill Rate: The fill rate seems to degrade as the variability in demand is increased. Systems 3 and 4 give good results for all system implementations. System 1 does not provide good results for all three factors, implying that holding stock centrally would be more useful if no transshipments are allowed. Otherwise, the system is capable of managing neither excess nor shortage. Since the weighted average fill rates are reflected as a total measure of performance in our system, it is not surprising that if $\mu_1>\mu_2$ and $\sigma_1>\sigma_2$, then greater amounts of generic inventory must be held for item 1 than item 2 to equalize the fill rates. Thus, postponement may be most effective when demand parameters of item offerings are close to each other.

Average % Backordered: The results for all system implementations are strikingly similar for low and high variation of demand. Having a higher coefficient of variation increases the chance of stockout. In all systems except System 2, the Tukey's groupings have been common for the low and medium demand variation instances. In System 2, the effects of transshipment for customized items seem to degrade the performance of managing demand variability. This maybe attributed to the fact that sending unique items creates more risk in managing inventory at the retailers. Since transshipment maybe carried out in anticipation or as a result of a stockout, it shows to degrade system performance in the systems.

Average Number of Transshipments: Transshipments appear to be an effective strategy in coping with demand variation. The amount of items transshipped is duely reflected in the systems that allow for transshipment (System 2, System 4 and System 5).

Average Total Cost: Not being able to foresee actual demand requirements is reflected in the increase of average total cost. Table 6.4 also reflects that all system implementations are greatly affected by this factor and are significantly meaningful. Overall, between low to medium demand variations, there is distinctively 25 % increase in average total costs. From medium to high demand variations the increase can be measured to be approximately 20%. Overall, working with high demand variation may result in at least 40 % increase in overall system implementation costs. If demand variability is high, overall inventory levels are lower in systems utilizing a postponement strategy.

6.2.1.4 Review Periods

The review periods for the central production facility and the retailers greatly affect the choice of system implementation. For the previous factors, some of the systems were often indifferent to factor levels. However, the review periods also give more striking results for most performance measures. System 1 and System 2 are insignificant for several levels implying that the systems are not properly utilized for these factor levels.

Average Order Lead Time: The order lead times for the customers are significantly affected by the review periods both at the retailers and the central production facility. This is also reflected in the performance of system implementations, as the flexibilities for the systems are better coordinated. System 1 gives distinctive results for each review period implementation, regardless of equal and unequal review period intervals. This is due to the fact that, System 1 is solely dependent on the central production facility for order fullfillment, it does not have an alternative strategy to cope with system deficiencies, if the retailers are out of stock. Overall, increasing the review periods at the retailers also degrades the performance of all the systems. System 5 does not seem to handle differences in review periods very well, since it is open to both mixed transshipment and stocking policies, the overall benefit of different review instances are not observed in the system.

Average Fill Rate: Postponement alternatives at the retailers help to improve system performance for different review periods. The retailers are able to cope better with end of period inventory shortages by working with uncommitted items. Otherwise, the systems without transshipment are least likely to cope with different review periods, making these systems more vulnerable to system disruptions, when the reveiw periods of the central production facility and the retailers are very close.

Average % Backordered: The systems give worst results when the review periods for the central production facility and the retailers are equal to five days. This could be attributed to the stock available at the retailers and the production facility within the five days of system review time. Postponement best manages the variability in review times offering more flexibility at end of reviews and best manages system stockouts.

Average Number of Transshipments: Since the central production facility holds two days and five days worth of inventory at unequal intervals it increases the available inventory at the retailers and thus increases the transshipment oppurtunities here as well. The overall average number of transshipments is lower than any of the systems defined which may imply holding generic items to benefit the system more than the other available transshipment strategies. The risk of inventory imbalance due to transshipments is duely reflected and greatly reduces transshipment activities.

Average Total Cost: The average total costs of the systems become a function of the available inventory level at the central production facility which is held for 1,2 or 5 days. The major holding cost is incurred in the central production facility, but since the retailers can satisfy their requests more easily and there is less need for rationing, the shortage costs that would have been incurred are balanced with the holding cost at the central production facility. The order costs also help diminish this effect as well. The service performance of the system is sensitive to the re-order level which is a function of the review periods. To generalize, provided that re-order levels are not high, higher service levels can be achieved without a significant increase in costs. However, the ordering costs are an important factor in overall cost comparison. Prior to the inclusion of this cost, the 5/5 review interval strategy was the highest in cost due to inventory backorder costs, but the difference has appreciably decreased due to ordering cost.

6.2.1.5 Transshipment Policy

The transshipment policy utilized has a discerning effect among the performance measures utilized. The results can be summarized as follows:

Average Order Lead Time: The order lead time of the systems with emergency transshipment are on the average less than those with preventive transshipment.

As preventive policies are often carried out in anticipation of possible stockouts, it may not be affecting the overall performance of the system as it may have created a greater risk of backorder for the item being transshipped from the respective retailer. System 2 performs best among either transshipment policy which implies that the true benefit of transshipment for the order lead time performance measure is best reflected in this implementation.

Average Fill Rate: For all the systems there is no distinguishing difference between either of the transshipment policies according to the Tukey's groupings. Since the fill rate is a function of satisfying item requests directly from the shelf, emergency transshipment has no affect what so ever. For the preventive policy, the timing and quantity of order initiation are critical; otherwise it is does not improve the average fill rate.

Average % Backordered: Emergency transshipment policies seem to better manage the amount of backordered items. This is in-fact a counter intuitive result of the systems simulation. This would in fact suggest that emergency transshipments have a role in tackling inventory imbalance within the total supply chain in the long run.

Average Number of Transshipments: System implementations are decisive in the amount of items being transshipped from one retailer to another. Overall, in System 1 preventive transshipments result in more items being carried from one retailer to the other. System 3 has more items transshipped for emergency transhipments, which would reinfore the importance of generic items being good substitutes for actual item requests. System 5 seems to favour stock redistribution in anticipation of possible stockouts (preventive transshipment).

Average Total Cost: Preventive transshipment is more costly for Systems 2 and 4. System 5 is indifferent to the transshipment policy utilized. This would suggest that the items being transshipped are delegated evenly according to product/item state (generic/customized) and transshipment policy which best satisfies retailer needs. It is intuitive that in a system where transshipment costs are very small relative to the holding and backorder costs, ignoring these costs when determining the inventory policy (review interval, order-up-to-level) may not lead to significant higher costs in the overall system. Moreover, if transshipment costs are equal to or greater than the holding plus backorder costs, then System 3 and System 5 would seem to be more preferable among the choice of systems with respect to average total cost considerations.

6.2.2 Generalizations for the main factor effects for the systems

Several generalizations for the main factors in the systems are as follows:

- **i.** Due to demand variability, as the order-up-to levels in the system rise, the extra cost of holding the inventory offsets the improved service level in the supply chain.
- **ii.** When demand variability is low, the performance of transshipment policies and thus pooling groups degrades. This could be attributed to the fact that backorders are not likely to occur early in the review period, however, when demand is variable, early stockouts at the retailers are more likely. Thus, in cases of high demand variability preventive transhipment maybe a more viable solution. Emergency transshipments often shorten average order lead times in the experimentations, which could be to compensate for long manufacturing lead times at the central production facility.
- **iii.** The choice of transshipment policy is important in system performance. The main distinction among the two policies is that since neither transshipment policy is instantaneous, the quantities transshipped are unavailable when they are in fact in transit from the central production facility and they cannot be used to satisfy demand at any of the retailers in a group at that time. Thus, lateral transshipment may result in actual deteroriation in total system performance if proper control buffers are not provided. In our system implementation, we provide this utilizing a threshold level for the systems.

- **iv.** In general, transshipments appear to be cost effective for supply chains with a large number of retailers, given that the transshipment cost is less than the sum of holding and backorder costs. Otherwise, the benefit of transshipment is foregone.
- **v.** Longer supply lead times from the raw material supplier to the central production facility often result in increased values for most performance measures like average order lead time, % of backorders, quantity of transshipments and average total costs.
- **vi.** The frequency and quantity of demand arrivals significantly affects the average total costs within the systems. Backorder costs are likely to increase due to partial fullfillment of orders.
- **vii.** For different demand variations, Systems 4 and 5 have similar costing structures, which would imply that they are more flexible in handling system variation and result in overall total cost. The variation in demand is handled through capabilities utilized such as form and logistics postponement.
- **viii.** When the review periods for the retailers and the central production facility are different, the amount of backorders in the system increases. Moreover, since there is less stock to exchange, the retailers become indifferent to any form of transshipment policy and decrease the amount of transshipments between each other. However, for systems with more than three retailers, they are more likely to request items from farther retailers. In most of the simulation studies, an interesting observation is that, the transshipment activities are usually carried out with retailers that are at most two retailers apart.
- **ix.** Postponement improves the fill rates; however, average order lead times become higher. Since both are customer centric measures, the tradeoff is important in system evaluation.
- **x.** An interesting observation is that as the number of retailers decrease, the average order lead time increases.
- **xi.** The effect of form postponement diminishes as the review periods increase making Systems 3, 4 and 5 similar.

xii. A policy at the retailers including either form and logistics postponement (Systems 2, 3 and 4 implementations) will allways perform better than a more standard system implementation such as System 1. Flexibility at the retailers allows better management of inventory and improves the overall customer service level.

xiii. As the retailers and/or central production facility order less frequently, the increased backorder/shortage costs may offset the lower ordering costs at the retailers.

xiv. Demand uncertainty leads to a discrepancy between raw material ordered and actual item requirements. This leads to underage/overage within the system implementations. The rationing policy may not produce good results for the system and may be critical in system evaluation. Other rationing rules maybe incorporated for better system implementation.

xv. The performance measures chosen are critical in the choice of five systems for supply chain implementation. Accordingly, the sensitivity of the five systems to the main factor implementations maybe summarized in Table 6.5 . For example, in order to improve the average fill rate in System 5, the demand variation should be decreased. Moreover, for System 2, in order to decrease the average % backordered, the number of items should be decreased and the review periods should be increased. Thus, Table 6.5 is helpful in selecting any system implementation among the five available with respect to the main factor levels.

6.2.3 Evaluation of interaction levels

An assessment of the interaction factor levels are detailed in this section. As seen on Table 6.3, most factor level combinations are statistically insignificant for most performance measures and the five different systems. This can be attributed to the fact that the interaction effects of several combinations override the benefit of either factor individually. Two distinctive factor level combinations give good results within the system which are (number of retailers*number of items) and (demand variation*transshipment policy) combinations respectively. The distinctive values for the significant interaction effects and their respective Tukey's grouping are seen in Table 6.6.

Table 6.5 Summary of main effects on the system implementations

	IMPROVEMENTS IN PERFORMANCE MEASURES AS FACTOR LEVELS CHANGE				
	Average Order Lead Time	**Average Fill Rate**	**Average % Backordered**	**Average Number of Transshipments**	**Average Total Cost**
System 1	NOR(+) ,RP(-)	NOR(-), NOP(),DV(+)	NOP(-), NOR(-)	NA	NOR(-), NOP(-), DV(-)
System 2	NOP(-), RP(-)	NOR(-), NOP(-),DV(-)	NOP(-),RP(+)	DV(+),RP(+)	NOR(-), NOP(-), DV(-)
System 3	NOR(+), NOP(-)	NOR(-), NOP(-),RP(-)	NOP(-)	NA	NOR(-), NOP(-), DV(-), RV(-)
System 4	NOR(+), NOP(-)	RP(+)	NOP(-)	RP(+),TP	NOR(+), NOP(+), DV(-), RP(-)
System 5	NOP(-)	DV(-)	NOP(-), NOR(-)	NOR(+),DV(+),RP(+)	NOR(-), NOP(-), DV(-), RP(-)

KEY:

NOR: Number of Retailers	NOP:Number of Products	DV: Demand Variation
RP: Review Periods	TP:Transshipment policy	NA: Not applicable

Change in factor level: INCREASE (+) ; DECREASE (-)

6.2.3.1 Number of Retailers and Number of Product/Items

This combination level is significant for all performance measures. To exemplify, the relevant effects, sample interaction plots have been used to demonstrate sample system performance.

Average Order Lead Time: The shortest order lead times are obtained through System 1 implementation. The average order lead time increases by more than 15% for System 4 and System 5 implementations. As seen in Figure 6.1, having four or six retailers has distinctively the same interaction effect on the combination levels, thus can be termed indifferent. When the lines are parallel in interaction plots, the interaction effects are assumed to be zero. As the slopes become distinctively different, the interaction effect has an important role on the results. However, in System 5 implementation, retailers six and eight seem to reflect the same effect.

Average Number of Transshipments: As the number of (product*retailer) combinations increases, so does the average number of transshipments in the supply chain system. The average number of transshipments increases more due to the number of retailers. Overall, when the number of retailers increases, the number of transshipments increases, however the type of items offered decreases.

Average Total Cost: The lowest average total cost for the systems is attained with System 3 which relies on pure form postponement at the retailers. However, System 4 implementations also give similar cost reflections, which would suggest that transshipment is a viable strategy in such product/item combinations. System 5 is higher in cost for the above mentioned systems, but gives distinctively better results with respect to Systems 1 and 2.

Average Fill Rate: The fill rate performances become worse as the number of retailers and the item combinations duely increase together. The worst fill rate performances are observed in the 8_retailer, 8_item combinations with average fill rate as low as 88 %. In the experimental settings, this value drops to 79 % for several scenario listings. Systems 3 and 4 greatly improve the average fill rates, as item/product combinations are better handled through generic product utilization and customization capacity at the retailers.

Table 6.6 Average System Performance Measures for significant interaction levels and results of Tukey's groupings

TWO FACTOR INTERACTION	LEVELS	Average Order Lead Time (minutes)					Average Fill Rate					Average % Backordered				
		SYSTEMS					SYSTEMS					SYSTEMS				
		1	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**
NOR*NOP	**4, 2**	10,04	10,02	10,90	11,02	11,20	96,72	94,84	97,10	96,33	95,64	10,29	12,33	6,57	6,38	5,57
		{3}	{3}	{3}	{2}	{1}	{3}	{3}	{3}	{3}	{3}	{1}	{2}	{1}	{1}	{1}
	4, 5	10,21	10,39	12,13	12,25	12,32	93,08	94,33	93,64	93,53	95,39	12,48	12,00	10,29	9,38	7,57
		{3}	{3}	{4}	{3}	{3}	{2}	{3}	{1}	{1}	{3}	{1}	{1}	{3}	{3}	{2}
	4, 8	10,54	10,61	12,13	12,27	12,45	95,12	93,55	95,44	95,64	94,16	14,86	14,27	10,59	9,82	8,36
		{3}	{3}	{4}	{3}	{3}	{3}	{2}	{2}	{2}	{2}	{2}	{3}	{3}	{3}	{2}
	6, 2	9,11	10,70	10,51	10,60	10,47	96,08	95,22	96,77	95,18	93,61	10,67	11,10	7,10	7,71	8,24
		{2}	{3}	{3}	{1}	{1}	{3}	{3}	{3}	{2}	{2}	{1}	{1}	{1}	{2}	{2}
	6, 5	9,28	9,53	10,44	10,55	10,62	92,79	93,37	97,00	96,38	93,91	14,05	13,81	8,14	8,33	10,33
		{2}	{2}	{2}	{1}	{1}	{2}	{2}	{3}	{3}	{2}	{2}	{3}	{2}	{2}	{3}
	6, 8	9,34	9,34	9,93	12,10	12,08	89,72	90,27	95,71	95,70	95,14	16,38	15,65	9,19	9,29	11,38
		{2}	{2}	{2}	{3}	{2}	{1}	{1}	{2}	{2}	{3}	{3}	{4}	{2}	{3}	{4}
	8, 2	8,18	8,18	8,49	9,70	10,12	92,92	92,65	96,15	95,94	93,48	11,67	11,76	7,62	7,24	8,48
		{1}	{1}	{1}	{1}	{1}	{2}	{2}	{2}	{3}	{2}	{1}	{1}	{1}	{1}	{3}
	8, 5	9,16	9,16	9,30	10,02	10,64	89,02	88,16	93,37	93,39	91,99	15,59	15,00	9,41	9,46	9,36
		{2}	{2}	{1}	{1}	{1}	{1}	{1}	{1}	{1}	{1}	{3}	{4}	{3}	{3}	{3}
	8, 8	10,29	10,29	10,83	11,93	12,28	88,90	89,17	93,12	93,09	93,02	20,10	20,00	12,76	12,10	12,05
		{3}	{3}	{3}	{3}	{3}	{1}	{1}	{1}	{1}	{1}	{4}	{5}	{4}	{4}	{4}

Table 6.6 cont'd Average System Performance Measures for significant interaction levels and results of Tukey's groupings

TWO FACTOR INTERACTION	LEVELS	Average Number of Transshipments					Average Total Cost				
		SYSTEMS					SYSTEMS				
		1	2	3	4	5	1	2	3	4	5
NOR*NOP	4, 2	NA	13,48	NA	21,24	12,05	1181,40	1230,90	1160,90	1202,70	1163,00
			{1}		{1}	{1}	{1}	{1}	{1}	{1}	{1}
	4, 5	NA	17,14	NA	25,24	16,19	1296,50	1325,50	1219,00	1238,80	1166,20
			{1}		{2}	{1}	{1}	{1}	{1}	{1}	{1}
	4, 8	NA	20,23	NA	27,82	17,95	1487,50	1509,10	1272,90	1300,50	1260,80
			{2}		{4}	{1}	{2}	{2}	{1}	{1}	{1}
	6, 2	NA	21,10	NA	23,00	18,14	1329,10	1363,00	1315,60	1367,90	1315,40
			{2}		{2}	{2}	{1}	{1}	{1}	{1}	{1}
	6, 5	NA	23,05	NA	22,05	19,29	1626,30	1654,60	1384,90	1419,80	1365,60
			{3}		{1}	{2}	{2}	{2}	{1}	{1}	{1}
	6, 8	NA	31,48	NA	19,86	20,62	1929,60	2069,40	1548,50	1594,90	1547,80
			{5}		{1}	{2}	{3}	{3}	{2}	{2}	{2}
	8, 2	NA	26,10	NA	28,57	25,86	1589,10	1658,40	1561,40	1639,60	1596,20
			{4}		{4}	{3}	{2}	{2}	{2}	{2}	{2}
	8, 5	NA	27,00	NA	26,05	29,23	1970,30	2049,40	1751,10	1788,60	1729,70
			{4}		{3}	{3}	{3}	{3}	{3}	{2}	{2}
	8, 8	NA	26,52	NA	26,29	26,52	2208,30	2268,80	1871,50	1932,50	1895,50
			{3}		{3}	{2}	{4}	{4}	{3}	{3}	{3}

Table 6.6 cont'd Average System Performance Measures for significant interaction levels and results of Tukey's groupings

TWO FACTOR INTERACTION	LEVELS	Average Order Lead Time (minutes)					Average Fill Rate					Average % Backordered				
		SYSTEMS					SYSTEMS					SYSTEMS				
		1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
DOV*TP	**Low, Preventive**	9,50	9,74	10,87	11,20	11,36	90,97	90,62	95,25	94,57	94,71	13,58	12,58	8,69	9,06	8,78
		{2}	{2}	{1}	{1}	{1}	{1}	{1}	{1}	{1}	{3}	{1}	{1}	{2}	{2}	{1}
	Low, Emergency	9,50	9,48	10,87	10,60	10,52	90,97	90,47	95,25	94,61	94,48	13,58	15,56	8,69	8,64	8,69
		{2}	{2}	{1}	{1}	{1}	{1}	{1}	{1}	{1}	{3}	{1}	{3}	{2}	{2}	{1}
	Medium, Preventive	9,92	10,42	11,36	11,64	11,92	94,53	93,83	95,76	95,43	94,29	13,31	13,00	8,61	7,92	8,50
		{3}	{3}	{1}	{2}	{2}	{2}	{2}	{2}	{2}	{3}	{1}	{1}	{2}	{1}	{1}
	Medium, Emergency	9,92	9,77	11,36	11,17	11,40	94,53	94,53	95,76	95,76	94,71	13,31	13,31	8,61	8,58	8,47
		{3}	{2}	{1}	{1}	{1}	{2}	{2}	{2}	{2}	{3}	{1}	{1}	{2}	{2}	{1}
	High, Preventive	9,64	10,18	10,93	11,14	11,51	91,96	91,97	94,33	94,28	92,28	16,22	15,36	11,56	10,83	11,25
		{2}	{3}	{1}	{1}	{1}	{1}	{1}	{1}	{1}	{1}	{2}	{3}	{3}	{3}	{2}
	High, Emergency	7,48	8,04	10,54	11,38	11,67	94,84	94,84	96,73	96,73	93,64	13,89	13,89	6,56	6,56	8,22
		{1}	{1}	{1}	{1}	{2}	{2}	{2}	{3}	{3}	{2}	{1}	{2}	{1}	{1}	{1}

Table 6.6 cont'd Average System Performance Measures for significant interaction levels and results of Tukey's groupings

TWO FACTOR INTERACTION	LEVELS	Average Number of Transshipments					Average Total Cost				
		SYSTEMS					SYSTEMS				
		1	2	3	4	5	1	2	3	4	5
DOV*TP	**Low, Preventive**	NA	14,42	NA	16,75	17,58	1368,40	1398,70	1178,20	1202,60	1170,40
			{1}		{1}	{1}	{1}	{1}	{1}	{1}	{1}
	Low, Emergency	NA	17,97	NA	25,97	19,11	1368,40	1421,80	1178,20	1259,90	1201,10
			{1}		{2}	{1}	{1}	{1}	{1}	{1}	{1}
	Medium, Preventive	NA	22,08	NA	25,11	18,53	1638,20	1671,40	1483,10	1498,40	1454,20
			{2}		{2}	{1}	{2}	{2}	{2}	{2}	{2}
	Medium, Emergency	NA	23,17	NA	31,53	16,72	1638,20	1707,30	1483,10	1537,00	1480,40
			{2}		{3}	{1}	{2}	{2}	{2}	{2}	{2}
	High, Preventive	NA	33,00	NA	21,92	28,69	1932,10	1988,60	1756,70	1778,10	1735,50
			{3}		{1}	{2}	{3}	{3}	{3}	{3}	{3}
	High, Emergency	NA	34,89	NA	29,44	29,00	1798,40	1992,10	1635,60	1766,80	1678,60
			{3}		{2}	{2}	{2}	{3}	{2}	{3}	{3}

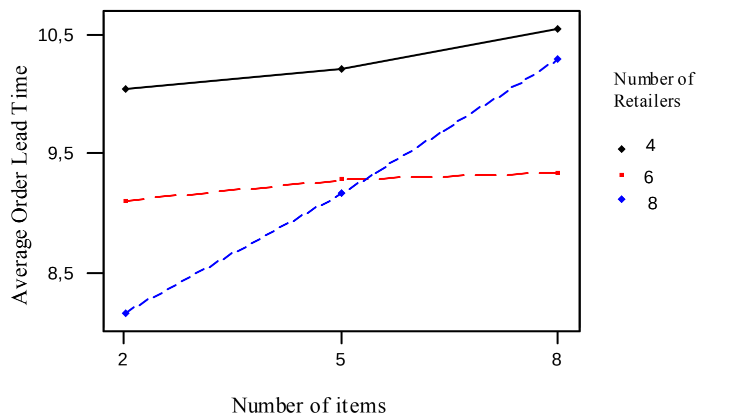

Figure 6.1a Interaction plot for average order lead time for System 1

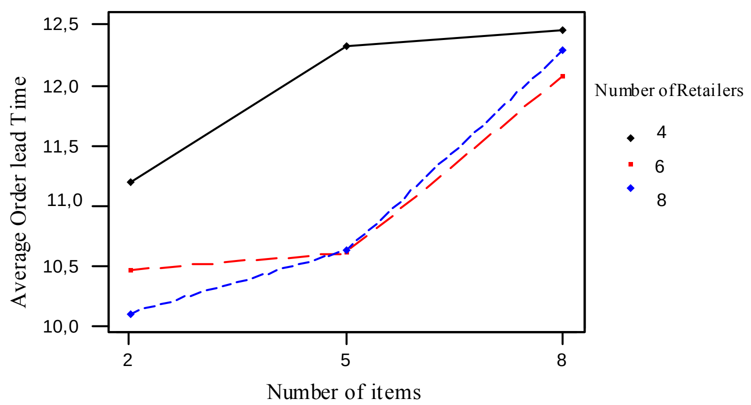

Figure 6.1b Interaction plot for average order lead time for System 5

Average % Backordered: The average % of backordered items is always lowest at the 2_item combination level. This is intuitive, since it is easier to find alternatives for two items rather than eight items within the supply chain. Overall, utilizing postponement may improve any product/item combinations by as much as 43% which is a very significant outcome of different system implementations. This effect may clearly be seen in the sample interaction plots in Figure 6.2a and Figure 6.2b, for System 1 and System 5 respectively.

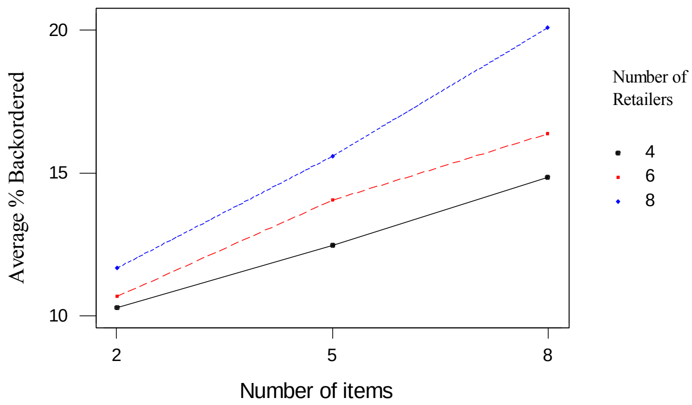

Figure 6.2a Interaction plots for average % backordered for System 1

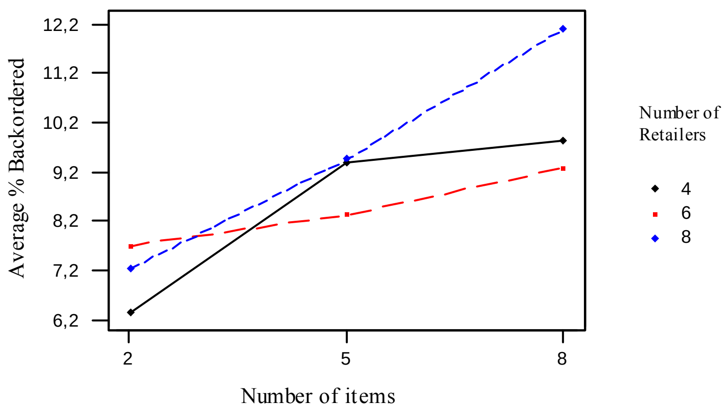

Figure 6.2b Interaction plots for average % backordered for System 5

6.2.3.2 Demand Variation and Transshipment Policy

Demand variation greatly increases the oppurtunities to utilize a transshipment policy. As demand variation causes surges in item demands, the best way to tackle with demand variability is to hold more inventory, in order to foregoe backorder costs which are more costly in most system implementations. Transshipment acts as an important medium to tackle with demand variation.

Average Order Lead Time: System 2 gives better order lead time averages in all combination levels with systems utilizing transshipment. The utilization of emergency transshipments decreases the lead times in most of the system implementations in respect to the preventive transshipment policy.

Average Fill Rate: System 4 gives better fill rates in all transshipment combinations. As seen in Figure 6.3 for System 4 and 5 implementations, the true effect of transshipment is less significant in low and medium demand variations. However, for System 5 which utilizes transshipment policies, the utilization of different item combinations (generic/cusotmized) and transshipment policies (emergency/preventive) is more apparent. An interesting point in Figure 6.3b is that in low demand variation, emergency transshipment degrades the performance in terms of the average fill rate, whereas in medium and high demand variations, emergency transshipments improve system performance.

Average % Backordered: Systems 4 and 5 with transshipment reduce the average number of backordered items by as much as 40% for both transshipment policies.

Average Number of Transhipments: The number of transshipments increases as the demand variability increases. The increase in the number of transshipments is also supported by an emergency transshipment policy utilized for any of the factor levels. Generic items are more likely to be transshipped in the supply chain.

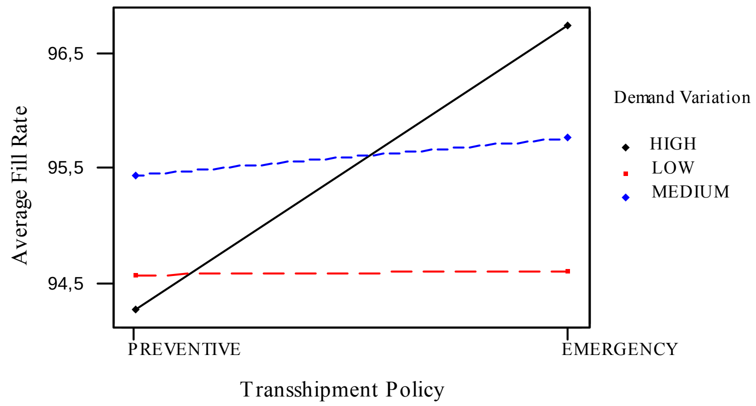

Figure 6.3a Interaction Plots for average fill rates for System 4

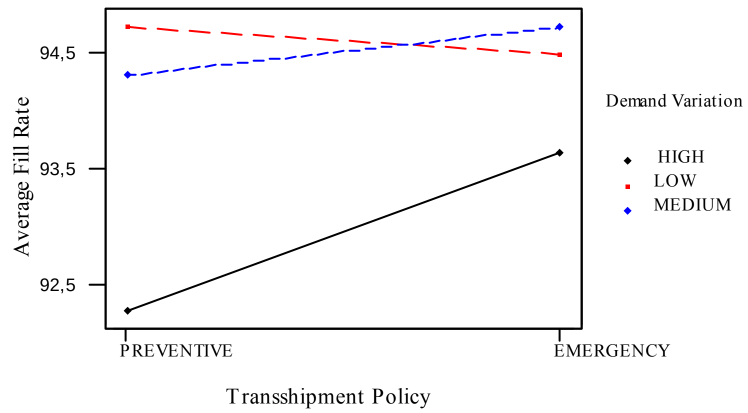

Figure 6.3b Interaction Plots for average fill rates for System 5

Average Total Cost: Systems 4 and 5 have significantly similar average total costs. For System 2, the cost difference between System 2 and either System 4 or System 5 implementations changes by as much as 18%, inclusive of ordering costs, 42 % excluding the ordering costs respectively.

6.2.4 Generalizations for main interaction effects for the systems

Several generalizations for the significant interaction effects for the systems are summarized below:

- **i.** As the review period increases, the benefits of postponement decrease for the number of retailers and number of item combinations with low levels (2 items, 4 retailers). The fill rate of the systems also degrades in such level combinations.
- **ii.** As the demand variability increases, the number of retailers becomes critical in overall system evaluation. As the number of retailers increase, there are more transshipment oppurtunities, however overall system costs may also increase due to ordering costs incurred at the distinctive retailers.
- **iii.** Demand variability may be availed of when the lead time for distribution, transshipment and production is small compared to the review period for the retailers.
- **iv.** In high demand variability conditions, the total cost is consistently higher than the total cost with similar review periods for the central production facility and the retailers.
- **v.** In high demand variation and high product/item variety combinations, transshipment of customized items is a risk as it makes System 2 more costly than any of the other systems.
- **vi.** If the number of items and the number of retailers are kept at a minimum, Systems 1 and 5 start to resemble each other. This would suggest that in these cases, the demand variation is manageable and no additional investment is needed for postponement.

6.3 Generalizations for various system implementations

Our study may give insights to companies that want to adopt postponement for different sector and supply chain structures.

These generalizations can be summarized as follows:

i. Postponement is a useful strategy for any single item having multiple item derivatives/combinations due to different language, technological specifications or market requirements. It reduces the total cost in all cases; however, the decrease is smaller when the variability in demand for different items are distinctively different.

ii. Form postponement is best utilized when there are no complex manufacturing activities at the lower echelon (retailers) and restricted economies of scale may be tolerated.

iii. If lateral transshipment is allowed, ordering for each retailer (respective lower echelon) independently may not be as optimal as ordering without provision for transfer.

iv. Transshipments eliminate the time wasted through lead time reductions. Instead of waiting for a new replenishment order or in-transit inventory, the order is handled faster. This property could support activities in a volatile market or supply chain context.

v. Postponement greatly affects the order lead time. Thus postponement is meaningful when item customization as well as logistics postponement can be carried out within a reasonable amount of time. Companies have different performance measures to evalute their supply chain structure. Accordingly, companies may combine measures of inventory availability (fill rate/backorder) and order lead time to produce a composite measure of service.

vi. Time is critical in postponement. Thus, acquiring and evaluating timely and rich information brings to attention the importance of designing organizational structures that are efficient in handling and processing this information. This would support better supplier replenishments and better allocations to the retailers. Working with centralized information or having an authority to delegate information could be an important factor in implementation of a postponement strategy.

vii. In the utilization of form postponement, it is better to reserve certain levels of capacity and resources to activities/item that benefit most from the additional information gained as a result of delay, since postponement pushes uncertainty to the lower echelon rather than completely eliminating it. Thus, System 5 implementation best fits this purpose. However, as the available capacity for this purpose decreases, the system dynamics resemble System 1 or a make-to-stock system. However, there is a tradeoff between the amount customers are willing to wait for and how much they are willing to pay for customization. Thus, the capabilities of the companies/retailers to produce customized items at a reasonable amount of cost and time are critical in postponement success. For example, higher utilization in System 1 may increase the positive correlation in the lead times of consecutive orders and accordingly reduces the value of inventory pooling in System 5 due to postponement.

viii. Joint utilization of the two postponement strategies maximizes the overall supply chain performance. For example, in the long run, firms willing to adopt both form and logistics postponement may achieve lower inventory levels with respect to the firms that only adopt a single postponement strategy which supports the role of System 4 and System 5 in our work.

ix. The proximity of retailers is critical in exchanging items across the same echelon. The in-transit time, production lead times and transshipment times are important factors that would entice or reduce transshipment activities among different retailers. Thus, if close retailers work together, they may act as a pooling group and reduce the total demand variability at the different retailers, thus reducing systemwide inventories.

x. Assumptions regarding demand distributions, order lead times and frequency of order arrivals are critical for various sector applications. Thus, for different sectors these may be more decisive in evaluating the overall supply chain performance. The study by Prasad *et. al.* (2005) demonstrates that developed countries rely more on stochastic lead times with known mean and variance, whereas developing countries rely significantly more on a known lead time.

xi. Companies willing to adopt postponement may do so selectively (for some products, or product families) if the production process is not suitable for complete postponement. If the company is part of an extended supply chain and coordinates several product/item groups with other companies, postponement would also be a meaningful strategy in such instances due to sharing of resources and more centralized demand and information coordination. In such a strategy, System 5 implementation would be more suitable.

xii. Inventory management policies are important in the implementation of postponement. Within a sector itself, management of different inventory items may prevent the adoption of postponement. For example, in the textile industry, sole fibre and textile industries most often utilize WIP or cycle stock, whereas retailers in the same sector work with customized items and prioritize safety stock. Accordingly, choice of inventory strategy may be important in overall system performance.

xiii. Industries such as the computer industry and automotive industry have immense suppliers and networks. Coordination amoung resources can best be managed through a postponement strategy utilizing the available network to offer different types of items and to eliminate redundancies in system implementations.

CHAPTER 7

CONCLUSION AND FUTURE RESEARCH ISSUES

Studies in supply chain management focus primarily on inventory management, whereas this study shows that other factors and policies may have a significant influence on system performance. Foremost, systems with multiple items and multiple retailers have been analyzed. Postponement has been a critical factor in improving supply chain performance as it allowed the firms to risk pool the uncertainty of demand for the items from all sources of variability (item and retailer/market). Five different system implementations have been included to show the striking difference among the use of two different postponement strategies, namely form and logistics postponement.

Simulation has allowed for more appropriate detailed analysis. Simulation was helpful in creating the systems and representing stochastic elements such as customer arrival and customer demand rates. The results of our study reveal that the five systems defined may act differently for similar settings, due to the effect and/or interaction of several effects. This has allowed us to define ideal operating conditions for different settings, which is important for companies in the selection of a system implementation. Overall, all of the systems are greatly affected by the increase in the number of items offered and the demand variation. The study has allowed comparison of the systems under several performance measures, which is important, as companies may prioritize different measures due to different scope of activities. The results have shown that postponement can be implemented for different sectors; however sector characteristics are important in differentiating a best postponement implementation (form, logistics or both). The study has also helped in distinguishing the effects of different types of postponement strategies in system implementation.

Future suggestions and possible areas for work may be summarized as follows:

i. In simulation verification and validation, the input parameters were altered to view system implementation; however these parameters were not included in the experimental framework. Different modelling assumptions for demand distribuitons, lead-time variations maybe incorporated in the study. Extending the model to include items with different lead times would increase the applicability of the model to different sectors.

ii. Although five distinctive system implementations have been carried out, factors hindering the adoption/implementation of postponement could be detailed for different production contexts for these systems. Sector-based distinctions in performance measures may be reflected in these observations.

iii. The life cycle of the item could also be critical in system selection and in the role of postponement in managing the deviation in item characteristics (demand, process utilization). In the study, the items were assumed to have predetermined demand characteristics throughout the simulation run.

iv. The role of customer involvement is critical in differentiating the value companies put to each distinctive customer requirement. Similarly, companies may rely on outsourcing strategies to outsource part or whole items and differentiating their core competence within a postponement context maybe critical. This may also bring to question the control of the supply chain and defining the role of the supply chain levels, from the manufacturer to the distributor which are possible areas of research. Within our study, a central production facility acted as a centralized authority for the retailers. Incorporating other authorities in the lower echelon and observing the system dynamics may also be a valuable contribution for future applications.

v. More accurate values for the re-order, order-up-to and review periods could have been utilized to observe the effects on inventory policy.

vi. In our study none of the items were allowed substitution. The overall inventory effects of substitution as well as prioritizing customer requests may be an important topic of concern. This maybe a unique topic of interest for interested parties working with perishable goods. Examples include the health sector (for blood transshipments) and FMCG (Fast Moving Consumer Goods) industry.

vii. Future research of postponement in service supply chains such as healthcare, travel and banking maybe researched as they uniquely rely on different performance measures. Different forms of postponement alternatives may also be analyzed for such sectors. As done in the study, different settings and system implementations maybe created and researched for the new sectors.

viii. The extended use of e-commerce/e-business activities are an important contribution to timeliness and quick response. The integration of such applications and tools to the postponement context could be analyzed. Utilizing such technology within the system implementations could have allowed easier access and control among the central production facility and the retailers in our study.

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