TWO WAREHOUSE MATERIAL LOCATION SELECTION

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by

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TWO WAREHOUSE MATERIAL LOCATION SELECTION

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ABSTRACT

As a company increases their use of warehouse, the excess inventory that cannot be stored in the owned warehouse are transferred to a third-party warehouse in which the company pays rent and transportation cost for storing items and moving items back to the production site. This research introduces the concept of material location selection that allocates materials to these two warehouses while minimizing the total storage and transportation costs. A two-warehouse material flow network model is formulated and then derived to generate five material location policies for evaluating the material flow situation of a real manufacturing company. The result showed that there is around 15%-40% cost saving that the company potentially obtains by systematically allocating materials to warehouses. A material location selection model is then proposed with a two-warehouse production planning model that accounts for workload dependent lead-time. In addition, an inventory rollback algorithm is given as means to bypass imperfect material movement information, in order to analyze inventory levels. Last, an application of the material location selection and production planning models is given as a potential extension of these models for determining an expansion size of the owned warehouse.

CHAPTER 1

INTRODUCTION

1.1 Background

1.1.1 Introduction to outsourcing and third-party logistics

As many companies nowadays start looking for new markets beyond their geographical areas, their business and manufacturing operations become more complex and sometimes hard to manage in detail by the companies themselves. In order to allow themselves to focus on their core-business functions, the companies start to look for outside service providers to help them manage some parts of their operations and acquire resources that are needed for running their businesses. Thus, the concept of outsourcing and third-party logistics (3PL or TPL) emerges.

The definition of 3PL has been discussed extensively in the academic literature. For example, Lieb et al. (1993) refers to the term when some or all logistics operations of a firm are managed by an outside firm; Rao and Young (1994) refer to the term used by the international 3PL industry as “bundle services for the movement of international freight”; Berglund et al. (1999) refers to it as activities that are performed by a logistics service provider and consist of “at least management and execution of transportation and warehousing”. A comprehensive list of TPL definitions can be found in Marasco (2008). Despite slight differences in definitions in the literature, third-party logistics services commonly involve outsourcing of logistics or logistics-related operations, such as order processing, item tracking, inventory management and customer brokerage.

Even though there are multiple kinds of services provided by 3PL service providers, according to Stanley et al. (2012), strategic related services such as supply consultancy, customer service and IT service tend to be less engaged, compared to tactical and operational services such as freight forwarding, transportation, customs brokerage, and warehousing. Among different types of 3PL services, warehousing and transportation are considered traditional services with high demand. Warehousing refers to the management of inventory while transportation refers to the process of moving items to points of need.

The beginning of 3PL services is hard to pinpoint since the term does not refer to any specific kind of service. However, its concept seemed to be embraced early by European firms and later spread throughout the US (Lieb et al., 1993). According to Berglund et al. (2000), the emergence of the 3PL industry can be traced back to the 1980's and can be separated into 3 eras:

1. 1980s: emergence of warehousing and transportation services
2. 1990s: emergence of express parcel deliveries
3. Late 1990s: emergence of other sub-logistics or logistics related services, such as finance, IT and management

Since the 1980's, the usage of the 3PL industry has continuously grown (Berglund et al., 2000; Lieb et al., 2004; Lieb et al., 2005). Also, the usage trend for 3PL services, including warehousing and transportation, are expected to increase (Ashenbaum et al., 2005). As part of the 17th annual survey by Langley and Capgemini Consulting (2012), who have been studying the 3PL market since 1996 through surveys of almost 2,400 industry executives across different global regions, it is reported that an average of

39% of the industrial logistics expenditure (12% of the industrial total sale revenue) was put into the 3PL or outsourcing industry in 2011. In addition, 65% of the respondents reported that their companies had increased 3PL use in 2012. Also, around 40% and 55% of warehousing and transportation spends were devoted for outsourcing, respectively.

Based on their 20th annual study by Langley and Capgemini Consulting (2016), they found that the percentage of industrial logistics expenditure put into 3PL services by the 3PL users surveyed was found to increase from 36% to 50% in 2015, and among different kinds of outsourcing activities, domestic transportation (80%) and warehousing (66%) are employed by most shippers who provided responses to the survey. As the 3PL market size seems to increase over time more research in this field is necessary in order to assess and evaluate the impacts, performance, and benefits of 3PL services.

The factors that drive firms to outsource their in-house activities include logistics and inventory cost reductions, core-business focus, market opportunity, and reduction in fixed asset acquisition (Rao et al., 1993; Langley et al., 2012). However, some firms may decide not to outsource their activities due to an activities' relationship to the core-business strategy, and the risk of losing control over specific items (e.g. dangerous material), and asset specificity (e.g. special equipment) (Rao et al., 1993; Ulrich et al, 2005, Langley et al., 2012). In addition, according to Ton Hien Duc et al. (2010) who studied the bullwhip effect and inventory cost in a supply-chain network with a third-party warehouse, they report that employing a third-party warehouse does not always lead to inventory cost reduction. The reduction depends on specific parameters in the demand process. Also, Burton (2013) suggests that current companies who outsource their operations, especially overseas, will reconsider their current need to outsource as doing it may lead to a 14%-60% hidden cost, due to changes in the world economic situation.

Deciding whether a firm should outsource their logistics or logistics-related activities involves measuring the trade-off among different factors (i.e. some of which are mentioned above), therefore, both qualitative and quantitative methods are needed not only to answer the question, but also to identify the extent of use, so that the firm can still retain profitability. In this research, we examine a warehouse problem in which a product manufacturer also owns a warehouse, but decide to outsource to another one through the help of a 3PL warehousing company in order to handle excess inventory. The main topic in this research is to determine how to allocate items across both warehouses, so that the outsourced warehouse and item transportation service are used in an optimal manner. In addition, we incorporate an option to bypass the outsourced warehouse by expanding the owned warehouse. This is based on the cost trade-off between outsourcing and owning the warehouse.

1.1.2 Warehouse management

In a supply-chain network, warehousing plays an important role as a stopping location where physical inventory, including both finished and unfinished goods, reside. There are two main types of warehouses in a supply-chain network: distribution centers and production warehouses. Distribution centers are used to distribute items/products to different demand locations geographically spread across the country. In contrast, production warehouses are used for storing production items, such as raw material, semi-finished goods, and some of the finished goods that are temporarily stored before moving to a distribution center. Therefore, a production warehouse is normally located at the manufacturing site or in close proximity to the production plant. In this research, we focus on the production warehouse and how it is utilized when another production warehouse is rented for excess inventory. Therefore, the term “warehouse” used in this research refers to a production warehouse rather than a distribution center.

A warehouse is used to enhance continuous production in order to enable better response to demand variability by having items stored for future use. However, warehouses can impact overall logistics cost negatively, since operating them comes with a cost. In fact, the warehousing cost is considered by the literature as one of the major four logistics costs aside from transportation, inventory, and administration (Rantasila et al., 2012). According to Wilson (2012), warehousing cost contributed around 33% of total US logistics expenditure ($1.28 trillion) in 2011. The cost to operate a warehouse includes, for example, labor, equipment and utilities. Consequently, many researchers attempt to reduce the warehousing cost through improvements in warehouse design and operation, such as storage layout, order picking, equipment selection, etc.

In addition to cost improvements, the operation response time of a warehouse is another concern that has been taken into account by researchers when trying to improve its performance. Having production halted due to lack of resources or parts for production may lead to a loss in sale opportunity and negatively impact customer satisfaction. To avoid these problems, work-in-process items (or in-process items) sometimes need to be stocked in the warehouse, but in turn they incur cost for managing and moving them around. Therefore, the concept of Just-in-Time (JIT) emerged to reduce the inventory while responsively handling the demand. JIT coordinates multiple manufacturing departments and processes (e.g. quality controlling, material ordering and warehousing), so that items are acquired and stored only as needed. The concept has been studied and adopted by large industrial manufacturers like Toyota Jidosha (Toyota Motor Corporation) and is closely related to lean manufacturing as they address waste reduction (Muda) in the system by eliminating non-value adding steps (Melton, 2005). Storing items and moving them between locations is considered wasteful, as they induce cost such as labor and handling equipment. Therefore, the amount of these activities should be kept to a minimum.

In order to both reduce the cost and improve the operational responsiveness, the topics on warehouse management, including both design and operation, have been extensively studied in the literature. According to Gu et al. (2007; 2010), warehouse design issues can be grouped into five interrelated areas: overall structure, warehouse sizing, department layout, equipment selection, and operation strategy selection. The overall structure concerns functions, resources and overall material flows of a warehouse. The warehouse sizing problem determines the warehouse’s size with respect to storage demand for inventory. The equipment selection and department layout problems determine which equipment (i.e. including storage equipment and material handlers) should be used in the warehouse, and how each department in the warehouse should be set up and arranged (i.e. pallet stacking height, number of aisles, and equipment locations – especially for AS/RS), respectively.

In contrast to issues that deal with strategic problems, warehouse operations focus on improving different kinds of activities performed in the warehouse, such as item receiving and shipping, order picking and item sorting. Among different types of activities, order picking is considered the most labor intensive task and accounts around

50-70% of the total warehousing expense (Berg et al., 1999; Charles et al., 2004; de Koster et al., 2007). Since warehouse operational performance is normally measured by total time or total travel distance taken by the item pickers for picking items, many researchers attempt to improve order picking operations through, for example, item batching, routing, item storage assignment and item zoning. One of the common goals that lead to improvement in the order picking process is to retrieve the item so that the demand is served as quick as possible.

Since designing and operating a warehouse involves many interrelated factors (e.g. layout, storage assignment, routing policy etc.), and due to the dynamic environment of the warehouse, the task of managing a warehouse is complicated, resulting in many management decisions that are made based upon the experience of warehouse managers or engineers (Hou et al., 2010). In order to help warehouse managers handle the operational complexity, warehouse management models and systems (tools) are developed by integrating and applying existing warehouse management concepts and techniques. Each model and tool has a different set of functions integrated within them, depending on their task-related purposes. Examples of these types of models and tools can be found Geraldes et al. (2008) and Hou et al. (2010).

One thing worth noticing is that the research on warehouse design and operation tends to focus on a single warehouse. In other words, they focus on internal issues of a warehouse rather than the design of a warehouse network. Refer to de Koster et al. (2007); Gu et al. (2007, 2010) for more comprehensive reviews on warehouse design and operation techniques. However, in the case that a company needs to store a larger number of items than its warehouse capacity, especially when the cost of acquiring materials is more than the cost of storage, the company may rent a warehouse or hire a third-party warehouse to handle their excess inventory (Pakkala et al., 1991; Bhunia et al., 1998; Yang, 2004; Zhou et al., 2005). If a warehouse is rented, the manufacturer will end up with two warehouses in the system. The existing research on warehouse design and operation does not address this issue. This leads to one of our thesis motivations. In particular, this research focuses on how to allocate items into two warehouses in order to minimize the space rent and transportation cost.

1.1.3 Two warehouse related problem

In a supply chain network where items are transformed through multiple locations visited in successive order, the warehouse is one of the business entities or locations that are regularly included in the network (Figure 1.1). It is normally referred to as a distribution center and follows the manufacturing entity (Tsiakis et al., 2001; Min et al., 2002; Seferlis et al., 2004). In contrast to a distribution center, a production warehouse used to store production materials is implicitly assumed to be integrated as local storage with the manufacturing entity. This assumption is generally true as long as each production site owns a production warehouse. Typically, each production site has a local storage unit, or production warehouse, in order to continuously respond to production demand and keep production running.

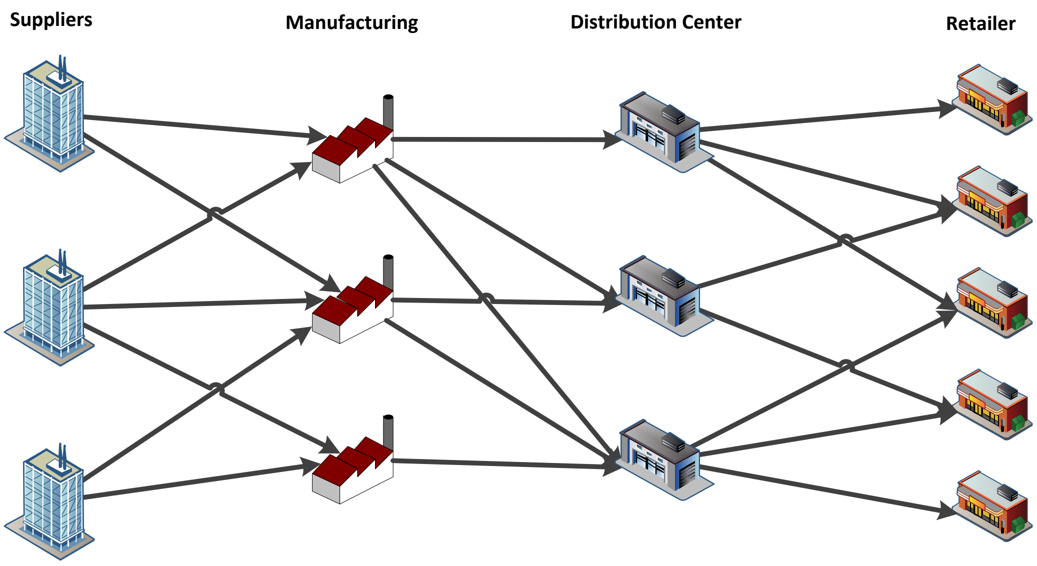

Figure 1.1 Supply-chain network

However, similar to any storage building, the owned warehouse has a finite storage capacity. Therefore, in the case that the owned warehouse is filled, the manufacturer may resort to a third-party warehouse in which they are charged for utilized space and item transportation for bringing items to the production site. The rented warehouse is called by different names such as overflow warehouse, rented warehouse, contract warehouse or third-party warehouse. Their meanings are slightly different with respect to potential additional services provided by each type of warehouse, apart from providing item storage. Nevertheless, the main purpose of renting a warehouse remains the same, which is to store items. Therefore, these terms are used interchangeably in this research.

In a traditional supply chain network, 3PL warehouses for production are not included, or not differentiated from an owned warehouse. Even though each rented warehouse only serves one local production site, this entity does not belong to the firm and also incurs cost, including space rent, item handling cost and transportation cost.

Production materials, including raw material, semi-finished goods, and finished goods, flow in-and-out between production facilities and warehouses unlike the warehouse/distribution center in the supply-chain network where items typically flow in one direction from upstream entities like suppliers to downstream entities like customers.

Also, the operational cost and storage environment of the rented warehouse tends to be different from those of the own warehouse (Bhunia et al., 1998; Yang, 2004). Because of these differences, deciding whether the rented warehouse shall be used or how much it should be used affects how firms manage their inventories and supply-chain performance. In the literature, the research topics that include decisions on using the rented warehouse have focused on inventory modeling.

1.1.3.1 Two warehouse inventory model

In addition to warehouse management, inventory management is another area of research that aims at reducing the inventory carrying cost, which is related to the warehousing cost. Researchers have attempted to bring the inventory carrying cost (i.e. inventory holding cost) down by determining a right level of inventory with respect to demand and operational cost (e.g. warehousing and transportation). The inventory models developed have been based upon different criteria, such as demand characteristic, i.e. deterministic vs. stochastic; replenishment characteristic, i.e. infinite rate vs. finite rate; number of commodities, i.e. single commodity vs. multiple commodities; number of planning periods, i.e. single period vs. multiple period; and types of items, i.e. deteriorating vs. non-deteriorating. A common goal among these methods is to determine when to purchase (restock) items and in how much quantity.

A two-warehouse inventory model problem deals with the creation of an inventory procurement policy for a two-warehouse system. In this research, the system consists of two kinds of warehouses; own warehouse (OW) and rented warehouse (RW). Due to factors such as seasonal price offers, seasonal product availability, and demand fluctuation, items may be purchased in large quantity that may exceed the capacity of the owned warehouse. This case can happen especially when the cost of acquiring items is relatively higher than the cost of storage or a significant income loss results from a production halt. In this situation, the manufacturer may decide to rent a warehouse from a third-party warehousing service provider to store the excess inventory. That is, when the inventory level is lower than the capacity of OW, the problem is reduced to a single-warehouse inventory control problem.

Similar to the inventory models (policies) with a single warehouse, the inventory models with two warehouses determine the item quantity to be purchased, but also with respect to the inventory holding cost charged by RW, whose capacity is commonly assumed to be unlimited. In addition, the inventory cost of RW is commonly assumed to be higher than OW. Therefore, the items in RW are used first before OW (Maiti et al., 2006; Hsieh et al., 2008; Lee et al., 2009; Liang et al., 2011).

Even though there have been many attempts to integrate multiple realistic criteria such as discount factor and item deterioration, most of the existing two-warehouse inventory models proposed in the literature deal with a single product. In fact, the inventory management problems with multiple products are hard to solve, due to the joint constraints that tie multiple product decisions together (Ghiani et al., 2004). Maiti et al. (2006) proposed a mixed non-linear programming problem to solve the two-warehouse inventory problem with multi-item inventory. However, the storage capacity of each item inventory is predefined. In other words, the locations where each item can reside are given beforehand in form of capacity limits.

In this research, we argue that without proper matching between items and locations, transportation and storage rental costs will not be optimized. This topic will be discussed in the next section. Later in Chapter 4, five mathematical models are developed to assign items to locations between an own warehouse and a rented warehouse, with respect to these costs. The results are compared against the actual storage operation of a real manufacturer that does not establish a material location plan, in order to observe the cost saving potential that the plan may provide.

1.1.3.2 Material location selection between two warehouses

As items are distributed between two warehouses, moving items in the rented warehouse to the production site induces cost, in addition to the space rent charged during the time items are stored there. While items of different materials are demanded with different rates, storing fast moving items (relatively high demand) in the production warehouse means frequent dispatching of items from the warehouse to the production site. Depending on how long each item is stored in the rented warehouse, the transportation cost per unit may be higher than the storage renting cost.

Figures 1.2 and 1.3 illustrate three sample inventories for materials A, B and C, and their replenishment cycles, respectively. If an onsite warehouse can hold up to 20 pallets, choosing material A to be stored onsite and the other materials to be stored offsite results in 100 pallet transshipments per month between offsite storage and production plant. In the opposite, choosing material C to be stored onsite results in 60 transshipments of material A and B between offsite storage and production plant.

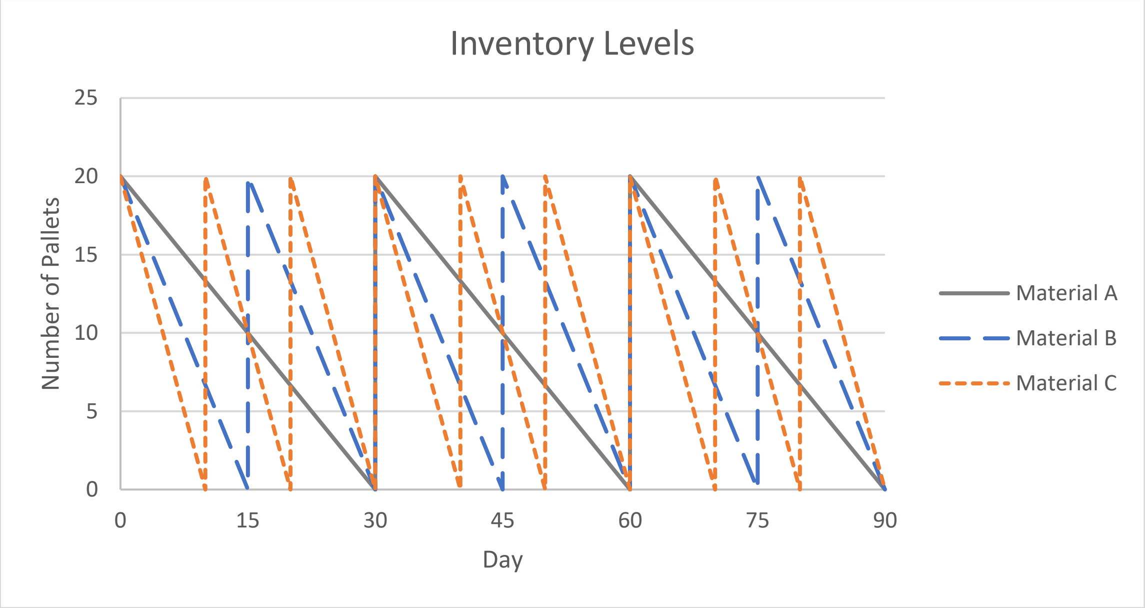

Figure 1.2 Samples of material inventories

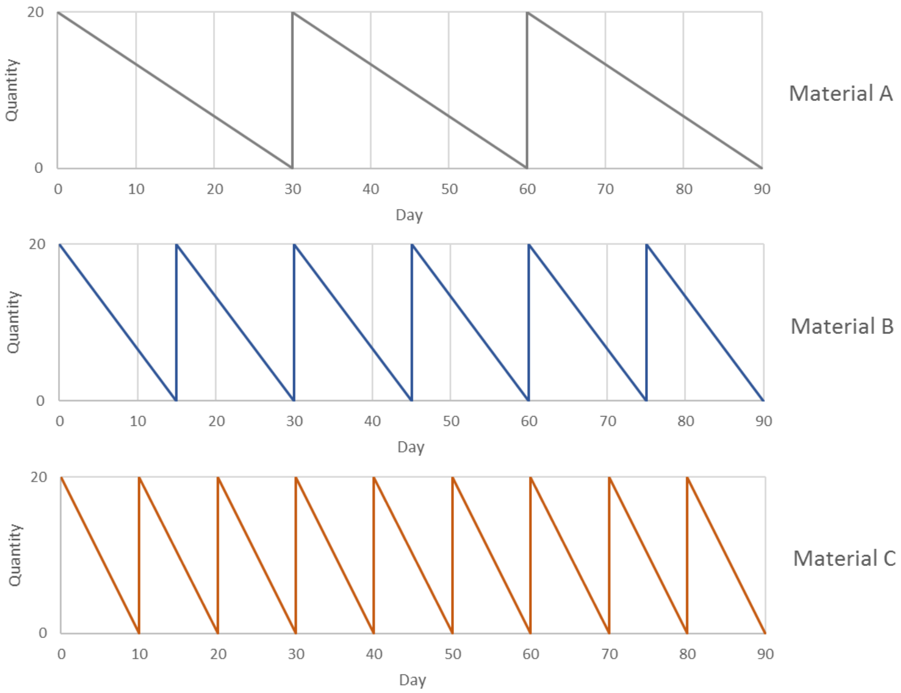

Figure 1.3 Replenishment Cycles

In addition to the difference in demand rates, the quantities and replenishment rates of each material are different. That is, some materials have higher numbers of items or consume more space than other materials. Storing high space consumption items of the same material in one location prevents items of different materials being stored in the same warehouse, leading to low material diversity in the warehouse. Consequently, some materials may be stored far away from their point of consumption, i.e. production plant. Therefore, efficient planning to determine where to store items and how much of their quantities should be allocated to each location will enhance the overall manufacturing operation in term of both cost and operation responsiveness.

In the literature, the problem of material location selection between owned warehouse and rented warehouse is basically non-existent. In the supply chain network design or facility location problems, the production warehouse is not considered unless they deal with the inventory management issues discussed in the previous section. However, the inventory management problem focuses on when and how much quantity to acquire for each material, not how to assign and arrange the materials between these two warehouses.

Furthermore, unlike a distribution center, a production warehouse is used to store items delivered for and produced from a production site. So, normally it does not appear as a separate entity in the supply chain network, unless it is used by multiple entities. However, in such cases, the warehouse acts similarly to a distribution center that distributes items to smaller distribution centers in a multi-echelon network (Tsiakis et al., 2001; Seferlis et al., 2004). The relationship between the production warehouse and production plant addressed in this research is illustrated in Figure 1.4.

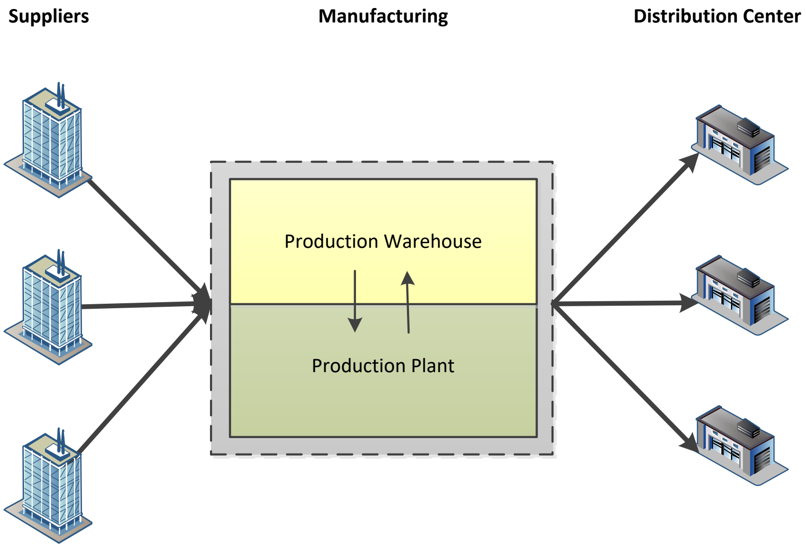

Figure 1.4 Manufacturing Entity in the Supply-Chain Network

In the case that a manufacturing firm rents a warehouse for excess inventory, a new entity, termed a rented warehouse, is introduced, but it works as an internal entity of manufacturing (Figure 1.5). This research addresses the operations inside this manufacturing entity. In particular, we try to generate material location selection policies to assign items or materials into these two warehouses so that transportation cost and space rental cost are minimized.

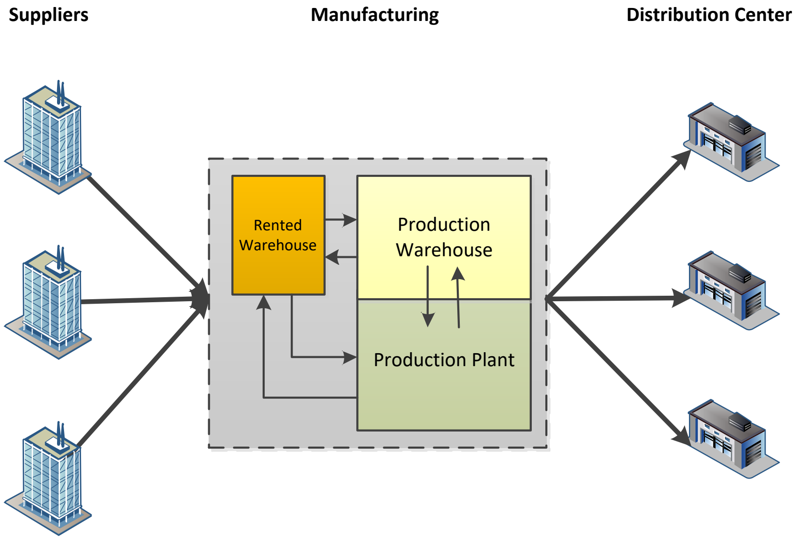

Figure 1.5 Manufacturing Entity with Rented Warehouse

1.2 Overview of the Research Problem

The problem environment consists of two storage locations; owned warehouse, also denoted as onsite warehouse, and third-party (3PL) warehouse, also denoted as offsite warehouse (Figure 1.6). The former location is located at the production site and has a limited capacity while the other location is located offsite and is owned by a 3PL who is responsible for storage space and material transportation between the offsite storage and onsite locations, including the production plant. In each time period, the 3PL warehousing company charges its client for the amount of space consumed and the quantity transported between onsite and offsite locations. Item procurement schedule and production demand are assumed to be deterministic and independent from each other.

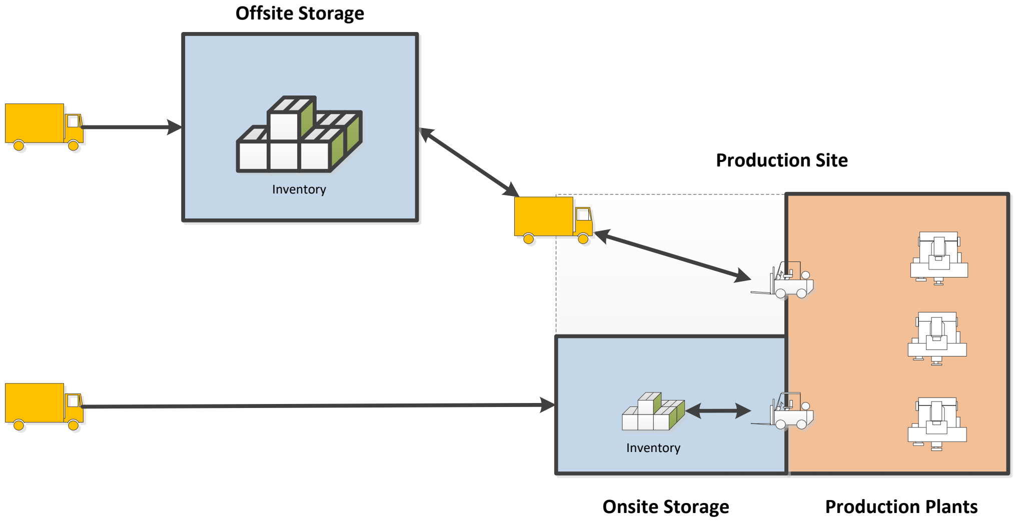

Figure 1.6 Two-Warehouse System

The problem is to identify the location of each item in order to minimize the overall transportation and storage costs while balancing the use of onsite and offsite storage. In the first section of this study, a linear programming model is formulated with a predefined production plan, outbound shipment and procurement schedules are used to calculate the cost reduction opportunity on the space rental and transportation cost charged by the 3PL in the case where the onsite storage is utilized according to these three schedules. Then, the model is extended and separated into four mixed integer programming models in order to explore different possible scenarios with different levels of decision restriction, and also to simulate different levels of flexibility that could affect operations of both internal and external entities, such as suppliers and inventory management team. Finally, the base model is extended and separated into a two-warehouse material location selection model and a two-warehouse production planning model, in order to allocate materials to storage locations and evaluate the material location plan with respect to production planning. A side application of the material location selection model is also given for solving the warehouse expansion problem. It serves as an exploration of another research direction that the problem of using the two warehouses can be extended to address.

1.3 Research Objective and Motivation

In order to effectively utilize the onsite storage space and not overuse the 3PL warehouse service, this research aims to minimize overall cost that is a function of transportation and storage rent by allocating items into both locations according to their levels of consumption and quantities. Several practical strategies are proposed that vary material storage and shipment restrictions. In addition, the research seeks alternative solutions to evaluate and possibly reduce the usage of the 3PL warehouse by allowing the onsite warehouse to be expanded and take advantage of production scheduling in order to determine the required level of 3PL warehouse space.

The motivation for this research can be summarized into three factors.

1. An actual material flow logistics project. The idea to initiate this study was inspired by an academic-industry partnership project initiated by Center for Excellence in Logistics and Distribution (CELDi) at University of Missouri (MU). The industrial partner was a branch of the global chemical and pharmaceutical company that develops and manufactures agricultural products. It produces the products to support markets across the globe. At the time, the company regarded the usage of its onsite warehouse capacity to be at maximum level and resorted to a 3PL warehouse that is located outside the production site, in order to be cost-efficient and convenient for managing items. The usage trend was expected to increase over time. After the CELDi team investigated and analyzed the usage and material flows of these two warehouses, it was found that the utilization of the onsite warehouse stayed lower than the actual warehouse's capacity throughout the observed period of one year. In addition, there were high volumes of items moving back-and-forth between onsite and offsite locations. The company was required to not only to pay for each consumed storage unit, but also for each item delivered to the onsite location. In order to reduce costs and improve material flow the team proposed that high demand materials be relocated to the onsite storage. In addition, additional issues such as the possibility of expanding the current onsite warehouse were raised by the company during the execution of this project.
2. Increased demand for outsourcing services. As reported in Lieb and Bentz (2005), the growth in demand for 3PL services has increased since 1991. In addition, the trend seems to be continuing to move upwards as the surveyed companies showed

their satisfaction with the services and interest to increase their use. While the usage continuously increases, almost half of the respondents reported that the services also have negative impacts on several management and operational issues such as employee morale, system development and logistic costs. Therefore, a method that balances the use of internal activities and outsourcing activities is necessary to ensure that companies are able to fully utilize the capability of resources they already own and to not become overly reliant on outsourcing services.

3. Lack of concern on the impact of material locations. The existing research on two warehouse related problems mostly deal with inventory control polices. The inventory models consider the case in which the owned warehouse does not have enough capacity to store excess inventory, causing the firm to employ a third-party warehouse for the overflow items. The rented production warehouse tends to be used as a secondary or second tier storage that replenishes the owned warehouse, i.e. primary warehouse, or have the items in the secondary warehouse to be consumed first. In other words, the rented warehouse can be viewed as an extension of the primary warehouse, whose list of items is either identical or sub-set of the items stored onsite. In fact, to the best of our knowledge based on the review of literature in Chapter 2, there is no literature considering the 3PL warehouse as the production warehouse that works in conjunction with the owned warehouse, and integrates it with the material-location selection problem. Because of all these issues, our problem is unique compared to the existing research.

1.4 Organization of the Dissertation

This dissertation is separated into seven chapters, including this chapter. In Chapter 2, the relevant literature is reviewed. The reviews are separated into four themes: warehouse management, two-warehouse related problems, production planning and warehouse sizing. Chapter 3 presents an algorithm to roll back a current inventory by using item (pallet) movement transactions. The results from this chapter are used in Chapter 4. Chapter 4 introduces the material location problem that allocates items to warehouses while minimizing total transportation and storage cost. It serves as the exploration of cost saving potential that an improved material location plan may cause. Chapter 5 presents a material location model, which assigns materials to the two warehouses. In addition, a two-warehouse production planning model is formulated as the material resource planning (MRP) that includes material flow and two warehouses. It is then used to compare different scenarios regarding the effect of considering the two warehouses, material flow and material location plan in the production planning. Chapter 6 shows a potential application of the material location plan model for determining warehouse capacity expansion. Last, Chapter 7 concludes the dissertation and provides areas of potential improvements as future work.

CHAPTER 2
LITERATURE REVIEW

2.1 Introduction

The literature review is separated into four parts. The first two sections briefly review the area of warehouse operation management and the two-warehouse related problems, in order to find the evidence that points to the use of a third-party warehouse. In particular, the first section assesses the existing topics that are related to using a third-party warehouse in conjunction with private warehouse while the second section reviews the two warehouse-related problems accordingly to the first section, in order to analyze the differences between the existing problems and the one proposed in this study. In the third section, the production planning problem is reviewed to investigate the opportunity to incorporate the two warehouse aspects into the production planning problem. Last, the warehouse capacity expansion problem is explored to observe the current practices that are used to justify whether a warehouse should be expanded in-house or outsourced.

2.2 Warehouse Management

Warehouse management refers to decisions which determine the functions and operations that are performed in a warehouse. It includes a wide range of topics such as warehouse sizing, storage assignment, item picking, and functioning area design. In this section, the articles reviewed from the literature are related to warehouse management problems. The chapter serves as a guide to the areas where the use of two warehouses seem to exist.

Then in Section 2.3, the topics that are likely related to the use of two warehouses are explored.

Berg (1999) mentioned the trend of supply chain management decisions is moving toward less inventory and high collaboration between different entities in supply chain system and internal operations of a company. The author focused the literature review on tactical and operational warehousing decisions. Some of the tactical decision related problems include assigning items to multiple functioning areas of a warehouse such as fast picking area (forward) and slow moving area (reserve), grouping correlated items for fast picking process, balancing workload across different item-picking zones, and assigning items to storage locations such as racks and bins. Some of the operational decision related problems include batching orders, creating pick routes, and determining idle location for automated pick/retrieval system (AS/RS). In another article, Berg and Zijm (1999) reviewed and discussed the operations research models related to these problems.

Rouwenhorst et al. (2000) reviewed the literature related to warehouse design and control and provide a classification of the topics in this area. The authors classified them into three hierarchical levels: strategic level, tactical level and operational level. The strategic level focuses on long term decisions such as process flow and storage system, while tactical level focuses on medium term decisions such as size of storage system and department layout. The operational level focuses on the actual processes in the warehouse.

Similar to Rouwenhorst et al. (2000), Gu et al. (2007) reviewed the current state-of-the-art in warehouse design and warehouse performance evaluation, but they grouped the topics into five interrelated areas with respect to each topic's type of decisions: overall structure, department layout, warehouse sizing and dimensioning, equipment selection and operation strategy. In addition, they also focus on how each reviewed literature evaluates the warehouse design performance. Also, as a companion paper, a comprehensive review on warehouse operations was done in a separate work (Gu et al., 2010).

de Koster et al. (2007) reviewed the literature related to order picking operations. Based on their work, picking operations account for more than half of the warehouse operations cost, and within that amount, 50% stems from travelling process for picking and stocking items. A comprehensive review was done on the problems that focus on reducing traveling time/distance, which also leads to reduction in throughput time, and on improving the efficiency of labor, space and equipment usages.

A comprehensive survey on the warehouse design problem was done by Baker and Canessa (2009). The authors summarized the steps taken by industries or found in publications for designing a warehouse. Along with a list of steps, they also identified the tools that can be used in each step. The steps range from gathering information related to requirements, determining facility layouts, and selecting planning and control policies. Their findings and additional information about the steps and tool were validated by and gathered from industry.

Based on the previous surveys, the research on warehouse operation improvement focuses on improving the internal operations of a warehouse, such as warehouse structure and layout, picking operations, equipment selection, etc. The topics in which the use of a rented warehouse with owned warehouse seem to exist are related to inventory modeling with the rented warehouse storing excess inventory, the forward-reserve problem, the two storage levels of tool magazines, and the supply-chain network. The next sections will present the existing work related to systems that consist of two warehouses. However, the reviews soon show that three of these four research areas focus on solving different problems and only use the second storage as a sub-component of their entire problem.

2.3 The Two-Warehouse Problem

2.3.1 Inventory models for two warehouses

The two-warehouse inventory model was introduced by Hartley (1976) in the form of two deterministic models. Goswami and Chaudhuri (1992) proposed two inventory models with two warehouses. The first model does not allow shortage and backlogging, but the other one allows both. The models deal with non-deteriorating items and incorporate the transportation cost for moving items from the rented warehouse (RW). The demand function is assumed to be a linear positive function of time.

Bhunia and Maiti (1998) studied the problem for deteriorating items with demand rate as linearly increasing function of time while both shortage and backlog are allowed. The proposed inventory model also incorporates the transportation cost for moving items from the rented warehouse house (RW) to the owned warehouse (OW). Yang (2004) proposed a two-warehouse inventory model with constant demand rate and incorporated the inflation rate into her model while allowing shortage and complete backlogging. Later, the model was extended to incorporate partial backlogging for the case that the demand for product during shortage is lost over time (Yang, 2006).

Zhou (2003) developed an inventory model that involves one owned warehouse and multiple rented warehouses with limited capacity. The model has a time dependent demand function that increases at a decreasing rate, and allow partial shortages to be backlogged. Later, Zhou and Yang (2005) created a two-warehouse inventory model whose demand function is a function of current stock level, as the authors believe that the number of customers purchasing items is positively related to the stock level. Also, the items are assumed to be transferred from RW to OW in a fixed time interval.

Maiti et al. (2006) applied a genetic algorithm to solve the multi-inventory model with two warehouses and no shortage. The demand function is assumed to be a function of selling price and advertisement frequency. Mondal et al. (2007) proposed a two-warehouse inventory model whose demand rate is dependent on stock-level, selling price, and advertisement frequency. Item transportation is assumed to be in a bulk release manner and shortage is not allowed.

Rong et al. (2008) considered the two-warehouse inventory model for a deteriorating item under fuzzy lead time and assumes that the ordering cost is partly lead-time dependent and OW is replenished by RW in a bulk release manner. Hsieh et al. (2008) developed an inventory model by minimizing the net present value and showed that the reorder interval is shorter than those generated by minimizing the average total cost. Jaggi and Verma (2008) proposed an inventory model with two warehouses and also try to jointly optimize both selling price and order quantity.

Chung et al. (2009) argued that the quality of items is not always perfect, so they incorporated an imperfect item quality effect into their two-warehouse inventory model. Lee and Hsu (2009) considered production cycle times to be variable and developed a two-warehouse inventory model for deteriorating items with time dependent, finite replenishment rate and finite planning horizon. Thangam and Uthayakumar (2010) considered the effect of a trade credit policy provided for retailers in their two-warehouse inventory model with price dependent demand.

Bhunia et al. (2011) developed a two-warehouse inventory model by assuming that the rented warehouse has a finite storage capacity and the demand rate is dependent on item selling, advertisement frequency, and inventory stock level. Liang and Zhou (2011) considered the two-warehouse inventory model with trade-credit effect and assume that the deterioration rate of OW is greater than RW. Dem and Singh (2012) proposed a two-warehouse production model that involves both perfect quality times and defective items. The demand for defective items is assumed to be dependent on the reduction in selling price. Ghiami et al. (2013) focused on the case of stock-dependent demand rate with deteriorating items, and applied the genetic algorithm to solve the problem.

According to the literature reviewed, four general remarks can be made. First, the existing inventory models for two warehouse systems normally deal with a single kind of items, or tries to create an aggregate production plan that considers an inventory level as an aggregate quantity of multiple item kinds. Second, the models implicitly assume that the rented warehouse works as extension of the owned warehouse. In other words, the owned warehouse is assumed to be filled first and then the items that exceed the warehouse’s capacity will be stored in the rented warehouse. Because of these problem characteristics, material location selection is not considered in this context.

Third, the problem assumes that the inventory stored in one of the warehouses is depleted first before using the other. This is different from the problem presented in this study as items, which are separated into multiple kinds, can be stored and drawn from any warehouse. Last but not least, since the two-warehouse inventory control problem considers items of multiple kinds as an aggregate unit, multiple item-flow directions are not captured in this aggregate level of planning. The impact of multiple flow directions in the operational cost will be shown in Chapter 5 as a two-warehouse production planning model is introduced.

2.3.2 Other two-warehouse related problems

In this section, the other topics related to usage of two warehouse, in addition to the two-warehouse inventory control problem, are discussed. These topics are briefly reviewed as it was quickly found that the concepts of two warehouses or multi-level storage found in the literature are not relevant to the two-warehouse material location selection studied in this research; either they are different applications or problems, or operating at a different level of business management hierarchy. Therefore, this section serves to support the findings about the usage of two warehouses in different context than the material location selection studied in this research. The topics included in this section are tool-switching, supply-chain network design, and warehouse forward-reserve areas.

In the production environment, the concept of two storage locations exists as a tool-switching problem (Matzliach et al., 2000). In this problem, storage denotes a location of non-consumable items or tools that are used by production processes or machines. The tools are stocked in the storage closest to the production line or machine's storage (i.e. primary storage). The primary storage commonly denotes a tool magazine that holds different types of machine tools. The excess tools that cannot be stored in the magazine are transferred to a secondary storage in which cannot be directly accessed by the production process. A set of parts (or jobs) to be processed is given. Each part is normally produced as a batch and requires a different set of tools than other parts. The tool sets may contain similar tools (or components). When the production process requests these tools, it halts and waits for the tools if they do not exist in the primary storage. While switching the tools, some of the tools in the primary storage (i.e. magazine) are removed. In this context, the problem is to minimize the time loss or cost incurred due to the switching process.

The nature and environment of the tool switching problem is different from the two-warehouse material-location selection problem studied in this research. Our problem considers consumable products and a material-location policy for the warehouse manager to follow, rather than optimizing a set of tools for a given set of tasks (i.e. denoted as jobs in the tool loading problem). More information on the tool switching problem can be found at: Tang and Denardo (1988) propose a tool switching policy called "Keep Tools Needed Soonest" (KTNS) policy to solve the problem with uniform size items; Matzliach and Tzur (2000) study the tool switching problem in which tools have different sizes and then proved that the problem is NP-Complete. Then, the authors provide two heuristic algorithms to tackle the problem; Hirvikorpi et al. (2006) extends the problem to include the cost of reorganizing and switching the tools in the primary storage; Carma et al. (2007) show that the problem with non-uniform tool sizes and known job sequence is strongly NP-complete.

The second topic found to use multiple warehouses is that of supply-chain network design. A supply-chain network refers to interconnected entities in a supply-demand system such as suppliers, manufacturers, and customers. The connections between entities represent flows of materials situated from extreme end of the network to another extreme end of the same network. For example, raw materials are supplied by a supplier to a manufacturer; then, the manufacturer acts as a supplier supplying materials to another manufacturer; in the end, materials, which may be processed and transformed through a sequence of transporting from one entity to another, are delivered at customer's location.

A large number of articles related to supply-chain network design exist in the literature. The problem focuses on efficiently and effectively capturing demands in the network and delivering items to customers in a timely manner. Jayaraman and Ross (2003; 2008) designed a distribution network that consists of distribution centers and cross-docks for consolidating shipments. Huang et al. (2005) focused on allocating products from multiple production facilities to warehouses, and allowed production capacity expansion. Shankar et al. (2013) developed an optimization model of the facility location and product distribution problems in four echelons supply chain network with single product. Sadjady and Davoudpour (2012) considered a two-echelon supply chain network, and proposed a heuristic algorithm to solve the manufacturing and warehouse location and sizing problems, and item distribution/allocation problem. Huang et al. (2014) explored the system in which a company can choose whether to provide a rebate for a retailer to accept early delivery or expand production capacity, in order to cope with demand fluctuation (i.e. seasonal product). Fattahi et al. (2015) incorporates price-demand relationship into the supply-chain network design problem.

Based on the reviews about the supply-chain network design, the problem considers the existence of multiple warehouses or distribution center. However, it looks at them from a macro level where they are used to store items to serving customers' demands in the network. As a result, items are moved in a single direction between echelons from upstream to downstream, such as from supplier to manufacturer or from manufacturer to retailer. The operational flow inside the manufacturing entity which typically include production storage or warehouse is omitted. This omission is expected since the focus of supply-chain network design deals with flow of materials through different echelons to serve customers' demands rather than focusing on the internal/local operations of each entity in the network. For addition details on supply-chaining management, the reader may refer to Beamon (1998), Min and Zhou (2002), Stadtler (2014).

Last but not least, the forward-reserve areas problem is another topic that deals with two level storage. Warehouse space may be partitioned into forward and reserve areas where the former stores items in relatively small picked sizes like cartons or bags and the later stores items in bulk size like a pallet. A manufacturer typically stores fast moving items (i.e. high demanded items) in the forward area and establishes the area close to the pick-and-drop-off location (I/O) for improving retrieval time, and replenishes the forward storage with items from the reserved area. The forward-reserve area problem refers to multiple sets of sub-problems related to the use of forward and reserve areas. The sub-problems include item assignment (i.e. determining item locations), item allocation (i.e. determining stored quantities) and area sizing (i.e. determining storage size).

Van den Berg et al. (1998) considers unit-load replenishments for the forward and reserve allocation problem by assuming that the replenishing period occurs before the picking period. Heragu et al. (2005) considers sizing different functional areas such as forward, reserve, and cross-dock while allocating items into the areas. Nguyen et al. (2005) studied the forward-reserve areas allocation problem with demand changes throughout planning horizon. Chen et al. (2007) briefly derived the satisfactory optimization model previously developed by Pu Yun et al. (2004) for modelling the forward and reserve allocation problem, and proposed a genetic algorithm as a solution to the problem.

Bartholdi and Hackman (2008) compared the optimal allocation to the strategies commonly used in the warehouse industry according to the authors' survey. Geraldes et al. (2008) analyzed the warehouse design and management of a private company, and then adapted the warehouse management model of Heragu et al. (2005). By analyzing the optimization model proposed by Hackman et al. (1990) for allocating items into forward and reserve areas, Gu et al. (2010) developed a branch-and-bound algorithm by using the outer approximation. Walter et al. (2013) studied the forward-reserve problem with discrete area size. Three different sub-problems were studied; allocation problem, assignment and allocation problem, and allocation and sizing problem.

According to the review, although the forward-reserve problem considers two storage areas and attempts to allocating items into these areas, both of them are non-identical in term of function, since the forward area stores small picked size items and the reserve area stores for bulk-size item and used to replenish the forward area. This means items in the warehouse flow in one direction. In addition, both of these areas are parts of the same warehouse and could be set up on the same rack (i.e. top shelves are used for bulk items and bottom shelves are used for small items). These are different from the two-warehouse problem where each warehouse operates in conjunction and items can flow between any warehouse locations. In other words, the internal setup of each warehouse (e.g. each has its own forward and reserve areas) is not the main focus in this research.

2.4 Material Resource Planning for Production Planning

Production planning is a generic term which refers to a process of managing production processes, including work release, and determining production quantities of materials. It is a complex process that involves multiple kinds of decisions such as order releasing, inventory controlling, process scheduling, and resource capacity planning. Each of these decisions is considered a research topic by its own. For this research, the material production planning serves as a means to evaluate the material location plan generated by the two-warehouse material location model presented in Chapter 5. Material resource planning (MRP) is chosen for this evaluation, due to its ability to include multiple materials in one model and consider bill of materials, which express item relationships, as well as shared resources. In this section, the literature related to MRP is reviewed. For additional information on the evolution of production planning see Olhager (2013) who broadly reviewed the literature related to production planning and control developed over the past five decades.

Material resource planning (i.e. MRP or MRP II) is an extension of material requirement planning (MRP I) that sequentially coordinates production of materials according to a Bill of Materials (BOM). It was created with regards to production/machine capacity, which is not accounted for in MRP I. Florian and Klein (1971) focused on a single product multi-period production system, and created a dynamic programming model that considers production capacities to be the same in every period. Hackman and Leachman (1989) developed a modeling framework for formulating a mathematical model for production planning. The model included generic constraints such as inventory balancing, demand satisfaction, and resource capacity. The modeling framework was then applied to formulate the material resource planning.

The disadvantage of using MRP is its lack of ability to associate production lead-time with resource workload, since lead-time typically increases non-linearly associated to the workload (Pahl et al., 2007) and their relationship is circular (Orcun et al., 2009). Zijm and Buitenhek (1996) attempts to estimate the lead time for a job-shop production by using queueing network techniques and considering statistical information related to production volume, lot sizes and product mix. Plenert (1999) discussed the differences between MRP and other production planning techniques, such as Just-In-Time, Optimized Production Technology, and Theory of Constraints. The author pointed out the benefits of using MRP include considering product variability, improving product trackability and ability to handle flexible production processes. However, it was also noted that the fixed workload-independent lead time of the classical MRP may lead to accumulation of inventory (i.e. inventory inefficiency), resulting in high carrying cost.

In the past two decades, there have been several attempts to incorporate uncertainty such as demand and item quality into the production planning, and associate the workload and lead time, and integrate them with production planning. However, due to their non-linear and circular relationship between workload and lead-time, and complexity for integrating uncertainness, heuristic approaches that approximates lead time based on workload such as using clearing function (Karmarkar, 1989) and meta heuristic like genetic algorithm are used.

To address the issue of workload dependent lead-time for MRP, Woodruff and Voss (2004) provided a conceptual optimization formulation that accounts for workload dependent lead-time. Asmundsson et al. (2009) proposed two mathematical programing models for single-stage and multi-stage production planning with workload-dependent lead time, respectively. They applied the clearing function technique that associates amount of work-in-process with resource throughput to limit the resource capacity. Although the models consider multiple products, they item dependencies are missing.

Kim and Kim (2001) combined the hybrid simulation-optimization approaches proposed by Byrne and Bakir (1999) and Hung and Leachman (1996) to capture fluctuation in production outputs and resource utilization, due to the workload dependent lead-time. The method spread an order into multiple periods (i.e. effective quantities) after it has been released. A fraction of an order that can be produced in a period is called an effective quantity. The effective loading ratios are repeatedly calculated by running the model and using its result in simulation for calculating new effective loading ratios.

Wang and Fang (2001) created an iterative algorithm to solve production planning with fuzzy product price subcontract cost, workforce level, production capacity and demand. Their model’s objectives are to maximize profit and minimize workforce level changes. The algorithm iterates with changes related to market information observed and added into the model by decision maker. Similar to Wang and Fange (2001), Wang and Liang (2005) developed an optimization model of aggregate production planning for the production system with stochastic demand, operating cost and capacity. Their approach focuses on minimizing potentially maximum total cost and possibility of getting higher total cost, and maximizing possibility of lowering it.

Aghezzaf et al. (2007) accounted for production system failure, which reduced production capacity. They integrated production planning with maintenance planning and focused on minimizing the expected production and maintenance costs. Orcun et al. (2009) considered stochastic demand in their production planning model with workload dependent lead-time, and attempted to determine the safety stock level. Kazemi et al. (2010) developed a multi-stage stochastic model for the production planning system that are subject to uncertainty in quality of raw materials, which results in uncertainty in production yields. Ravindran et al. (2011) integrated order releasing and safety stock problems into the production planning of a single product and used a clearing function to capture workload dependent lead-time.

To capture uncertainty in job-shop production system, Georgiadis and Michaloudis (2012) developed a real-time production monitoring system that integrates production ordering and batch sizing. Baykasoglu and Gocken (2012) formulated a mixed integer programming model for planning production by separating it into two phases with the first phase producing items and the second phase assembling the produced items with purchased items. A genetic algorithm and tabu search are then used to solve the problem.

Brahimi et al. (2015) integrated production planning with order acceptance decisions and accounted for workload dependent lead-time. A mixed integer programming model was formulated with two decomposition-based heuristics for solving the problem. For additional information on workload dependent lead-time, comprehensive reviews on production planning with workload dependent lead-time and workload control can be found in (Pahl et al., 2007), (Thürer et al., 2011) and (Hendry et al., 2013).

According to the above survey, the production planning problem has been expanded extensively since the introduction of the basic optimization model proposed by Hackman and Leachman (1989). Researchers have addressed workload dependent lead-time and uncertainty aspects of the production system. The focus has ranged from single products to multiple products, deterministic demand to stochastic demand, and constant operating cost to fuzzy operating cost. Although most of these models consider inventory holding cost that is situated in warehouse or production site, they do not mention where items are stored nor the existence of another warehouse which may be located off the production site. In other words, items are assumed to be present at the production site once they are needed without considering how they are delivered. In the context of using one warehouse located onsite, since all materials are stored in one location, their transportation cost can be considered as sunk-cost or sufficiently small enough not to affect production decisions. However, as will be shown in Chapter 5, when materials are stored in the rented warehouse which is commonly located outside production site and has different carrying cost rate than the owned warehouse, considering both warehouses versus a single warehouse in the production planning can result in different inventory holding and transportation costs.

2.5 Warehouse Storage Capacity Expansion

The warehouse sizing or storage capacity expansion models that have been studied and developed in the past three decades are widely formulated as a variation of the economic order quantity model (EOQ), which determines the item reorder quantity that minimizes inventory related costs. This type of EOQ assumes the additional storage space is available through leasing from a third-party logistics provider. The ones that incorporates different holding cost rates at two warehouses, in particular, have been reviewed in section 2.3.1 and will not be repeated here. In this section, the EOQ models that consider the leased space as an extension of the existing warehouse or don't differentiate the inventory holding cost rate are reviewed, along with some of the other works related to the warehouse storage capacity expansion.

White and Francis (1971) studied the multi-period warehouse sizing problem in both deterministic and probabilistic demand environments while considering the cost of storage construction, storing and a penalty for the items that cannot be stored in a warehouse. Bhaskaran and Malmborg (1990) developed a stochastic cost-saving model to partition a warehouse to active pick area (i.e. forward area) and reserve area while considering storage cost, cost of picking and cost of replenishment in the active area. Heragu et al. (2005) developed a mathematical optimization model and a heuristic algorithm that determine the sizes of forward and reserve areas, and also allocates items into these areas.

Cormier and Gunn (1996a) proposed a static model for determining warehouse size and associated inventory policy with constant product demand. Then, the authors (1996b) extended their work to include a choice of leasing item storage. Later, a dynamic programming model for warehousing size planning that considers a multi-item inventory policy was proposed (Cormier and Gunn, 1999). The model was developed by applying the multi-item inventory policy that accounts for ordering and inventory holding costs, and does not allow backordering

Rao and Rao (1998) extended the static warehouse sizing model from the literature to account for time-dependent cost, economies of scale in capital and operational expenses, and stochastic demand. Then, the dynamic model for warehouse sizing was adopted from the literature and shown to be a network flow problem. Goh et al. (2001) consider the space leasing cost as a step function and develop two closed-form models, one for a single material and the other for multiple materials with material dependent inventory holding cost rates. Chen et al. (2001) incorporated the base commitment charging rate that applies to each unit of items up to a certain number of items stored in the warehouse and then the extra space usage is charged a premium rate.

Lee and Elsayed (2005) formulated a non-linear programing model to determine warehouse size and the amount of leased space under the dedicate storage policy, and tried to minimize the total cost and satisfying the required service level. Later, they provide an iterative search heuristic to solve the problem. Cheng et al. (2009) incorporated warehouse capacity as a decision variable into the EOQ model, and assumed that warehouse cost like rental and labor costs is substantially higher than non-warehouse inventory holding cost like inventory investment and insurance cost. Two EOQ models were given with one considering a divisible production and the other considering a non-divisible product.

Based on the literature reviewed done in this section and section 2.3.1, the existing warehouse sizing models do not incorporate the material selection problem. In fact, when an option for renting a warehouse exists, the rented warehouse is considered as an extension of the owned warehouse for storing excess inventories of materials that are purchased in relatively large quantities, in order to take the advantage of on-going deals or economy of scale (i.e. purchase in large volume for lowering per-unit price). In summary, the problems considered in the reviewed articles, both in this section and section 2.3.1, focus on how much additional space should be rented as a result of inventory purchased or produced, and do not answer how much space should be added to the owned warehouse in order to balance the use of both warehouses.

2.6 Summary

In this chapter, the articles that surveyed different problems in warehouse management were reviewed to find the usage of two warehouses. Four different problems known as two-warehouse inventory control, two storage-level tool switching, supply-chain network, and forward-reserve areas were found that they consider more than one area of storage locations. However, the reviews quickly showed that they focus on solving different problems and are not directly related to the two-warehouse material location selection problem studied in this research. Although the two-warehouse inventory control explicitly deals with the use of a rented warehouse in conjunction with the owned warehouse, the differences between this problem and the two-warehouse material location selection problem are their problem focus and usage nature of both warehouses. In addition, most of models reviewed for the former problem determine an ordering amount of a single material, rather than storage locations of multiple materials.

In addition to reviewing the two-warehouse related problems, this chapter reviewed the articles related to production planning and warehouse capacity expansion. The review showed the existing production planning models do not consider the storage location and transportation activity of materials, and location-dependent inventory holding cost rate, which is the result of different material handling capabilities between warehouses. In addition, the existing capacity expansion problems reviewed mainly refer to the rented warehouse as a means to obtain additional storage space, rather than installing/adding it into the owned warehouse.

To fill these gaps, this research studies the problem of assigning items into the owned warehouse and rented warehouse with consideration on transportation cost and different inventory cost rate incurred at each warehouse. In addition, the traditional production planning model is expanded to include both of these aspects. The two-warehouse material location selection and production planning models are then used to determine additional storage space that should be added to the owned warehouse, in order to balance the use of these warehouses.

In the next chapter, an algorithm used to reconstruct the warehouse usage profile from time-stamped data is developed. The results of this algorithm are then used in Chapter 4 for analyzing the warehouse utilization level of a real manufacturer, in order to identify the real-world motivation of solving the problem. In Chapter 5, a two-warehouse material location selection model is proposed, as well as the two-warehouse production planning model. As a side application, these two models are used to determine addition warehouse capacity in Chapter 6. Then, the research is concluded in Chapter 7 with mentioning on potential areas for extending this research.

CHAPTER 3

INVENTORY ROLLBACK

3.1 Introduction

To assist in the evaluation of the models that will be introduced in subsequent chapters, inventory information such as inventory counts and item movements was collected from an industrial partner. This data is required to assess the improvement in terms of rental and transportation cost savings due to changes in material location. However, the company only kept a snapshot of inventory once a month, resulting in periods where the warehouse usage is unknown. In order to analyze the warehouse utilization and prepare data for the models in Chapters 4, the current inventory was rolled back according to the historical item movement transactions recorded in the company's SAP system. Note all items in this research are measured in pallet units.

The historical movement transactions were recorded by workers through either computer or bar-code scanner prior to the actual movement of items (i.e. pallets). Intuitively, the inventory roll-back process starts from the latest movement transaction prior to a snapshot of the inventory, and then traces back through time according to the timestamp of each movement transaction. While moving backward to retrieve snapshots of past inventory, the inventory of each location is reconstructed by either adding or subtracting the quantity associated with each transaction to the current inventory. The process repeats until no item movement transaction can be found (Figure 3.1). A drawback of this process is that it assumes all movement transactions represent actual movements. However, due to the fact that the item movement data is not designed for rolling back the inventory, but rather to capture human activities and decisions, any changes in decisions on item movements or human-related error are hard to avoid, causing the incorrect data to be entered into the system. Consequently, if the inventory is rolled back according to this scheme, the process might come to a halt at a transaction that does not represent an actual movement or does not have a relationship with other transactions, resulting in a break in the item movement flow during the rollback process (Figure 3.2).

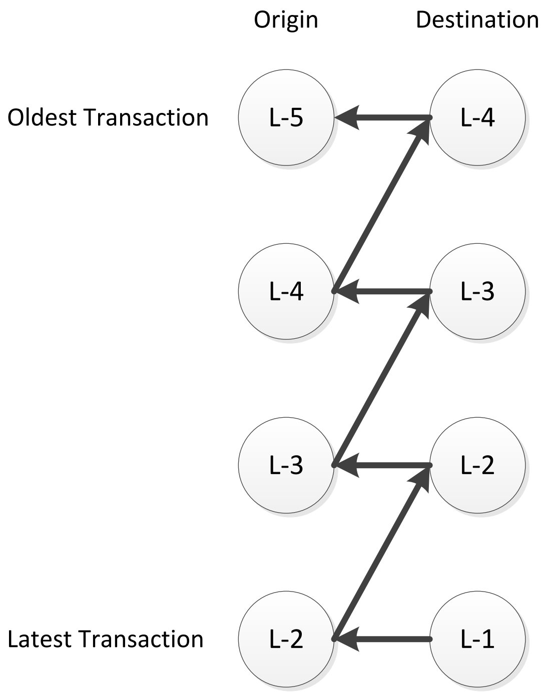

Figure 3.1 Inventory rollback process with perfect linked flows

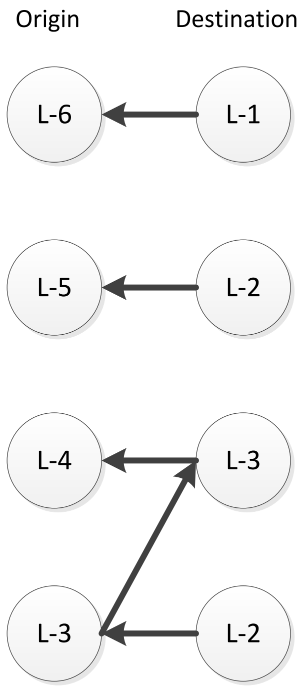

Figure 3.2 Inventory rollback process with broken flows

To solve this problem, this research proposes a generic method to estimate the past inventory by using item movement transactions to roll back the current inventory. Even though this method is only a preparation process for the data that will be used in the next chapter, we believe that its usefulness can be applied to other inventory-related problems in order to analyze the utilization of warehouses. The method is generic and can be applied with time-stamped data that specifies locations of where the data is captured.

3.2 Inventory Rollback Approach

In this section an algorithm to roll back the current inventory is introduced. The rollback is used to estimate the inventory stored in each location within each specific time period. The algorithm requires (1) a snapshot of current inventory, and (2) item/pallet movement transactions. The first data determines an origin location of a path graph, which is a route for each pallet. The movement transactions are used to construct a directed graph. In addition to these two data, a snapshot of past inventory can be used to determine a destination location of a path graph for each pallet, but it is not required for running the algorithm. It is only used to enhance the solution that will be selected by the algorithm.

3.2.1 Inventory rollback algorithm

The inventory rollback algorithm developed in this research constructs a multi-level directed graph for each item pallet and then searches for the longest possible path that traverses through the graph. The algorithm can be described as follows:

> STEP 0: For each pallet, sort all pallet movement transactions by their timestamp from the oldest to the newest.
>
> STEP 1: Construct a directed graph according to the following:
>
> > STEP 1.1: For each transaction, create two nodes; one for origin and the other for destination.

STEP 1.2: Create a directed link between two nodes of the same transaction in a reverse direction from destination to origin.

STEP 1.3: Between any two consecutive levels, create links (edges) with one unit weight/length from lower level nodes to upper level nodes that represent the same location and have the same pallet identifier.

STEP 1.4: Created directed links with negative one unit weight/length from lower level nodes to upper level nodes, but not in the consecutive level. Both nodes of the same link have to represent the same location and have the same pallet identifier.

STEP 2: Reverse all edge weights by multiplying them by minus one.

STEP 3: Solve the shortest path problem from the node that is in the bottom level of the graph and also represents the location in which the pallet is currently stored. If such node does not exist, then move up to another level until such node is found.

STEP 4: Select the overall longest path, or select the longest path whose end is the node that represents the location shown in the past inventory (if applicable) and occurred on the same date as the past inventory.

STEP 5: Traverse the longest path. While moving from one node to another, delete the pallet from the current inventory of the origin location and add it to the current inventory of the destination location.

The directed graph constructed in step 1 connects the pallet movement transactions together. The algorithm tries to traverse through the graph as far as possible by solving the longest path problem, in order to connect all transactions together.

Normally, the complexity of the longest path problem is NP-complete. However, there is a topological sort of the graph constructed by the rollback algorithm (Theorem 1). Therefore, the problem can be solved in polynomial time by using either the DAG shortest path algorithm or Bellman-Ford algorithm with reversed edge weights.

Lemma1. Given a directed graph *G(V, E)* constructed according to step 1 shown above, where V is a set of nodes and E is a set of edges. G contains no cycle and is directed acyclic graph (DAG).

Proof: As the graph is constructed in right-to-left and bottom-to-top manner, where each level contains exactly two nodes, there is only one right node and one left node in each level (right-to-left) and all cross-level links have an upward direction (bottom-to-top). Suppose that *G* contains a cycle and there is a path from node *u* to *v*. Then, node *u* is either a right node of node *v* or a node lower than node *v*. Having a path back from node *v* to node *u* contradicts one of the two assumptions given above.■

Theorem 1. Given a direct graph *G(V, E)* constructed according to the rollback algorithm, where V is a set of nodes and E is a set of edges. G has a topological sort that moves from right nodes to left nodes in bottom-up manner.

Proof: According to Lemma 1 that *G* contains no cycle and by the convention used to create *G*, the theorem can be proved by the induction technique. In level 1, the left node is reachable from its right node, but not the other way around. In addition, these two nodes are not reachable from any upper nodes, since downward connections are not allowed by the convention. Therefore, both nodes in the first level are in a topological sort by having the right node come before the left node. In the second level, one or both two nodes can be reached by the lower level nodes and the left node is reachable from the right node, but again not the other way around. Thus, a topological sort can be created by putting the right node and then the left node after the first level nodes. The proof then repeats with the third level, and so on. In the final level, the proof remains the same, except that no nodes can be reached by the nodes in this level (Lemma 1). ■

Table 3.1 Sample of pallet movement transactions

Date	Origin	Destination	Origin Pallet	Destination Pallet
1/1/2010	RCPT	L-1	A	A
1/2/2010	L-1	L-2	A	A
1/2/2010	L-2	L-4	A	B
1/5/2010	L-1	L-3	A	A
1/10/2010	L-3	L-2	A	A

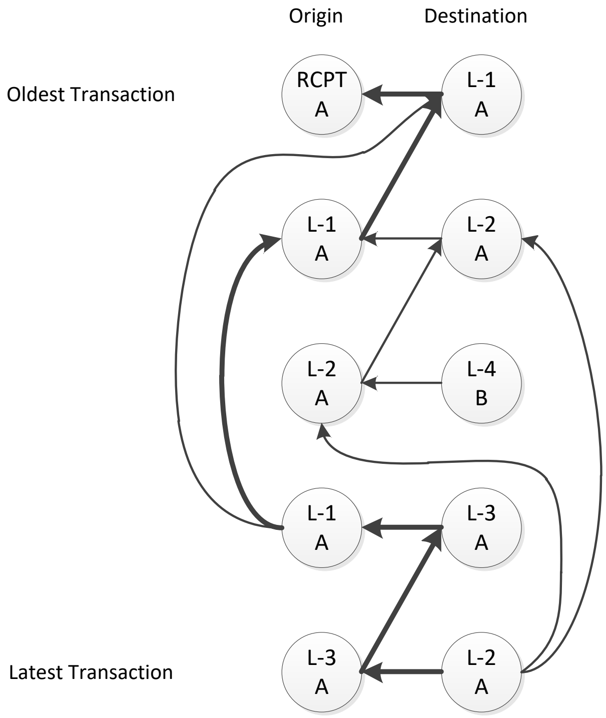

Figure 3.3 An example of the inventory rollback graph for pallet A with four transactions

To explain the logic behind the algorithm, Table 3.1 and Figure 3.3 show an example of pallet movement transactions and the graph constructed by the algorithm, respectively. The graph is constructed for pallet A with five pallet movement transactions recorded. There are five locations, RCPT (i.e. receiving dock), L-1, L-2, L-3 and L-4, involved in these transactions. The pallet identifiers are shown underneath the location names, and the longest path is shown with bold lines. According to the transactions, two movement activities were registered to be executed on 1/2/2010 (e.g. moving from L-1 to L2 and then getting split at L-2 and transported to L-4), but they did not happen. In the next day, the warehouse operator decided to send it to L-3 instead. By constructing the network graph based on the inventory rollback algorithm (Figure 3.3), the unexecuted or error transactions on 1/2/2010 were bypassed by the edges that connect nodes across levels. According to the longest path, the pallet was received in L-1 and stayed there for some time before being moved to L-3 and then L-4, in that order.

3.2.2 Computational complexity and discussion

The idea behind the algorithm stems from the basic approach discussed in Section 3.1. If all pallet movement transactions perfectly represent the actual moves of pallets, the rollback process shall include all pallet movement transactions (Figure 3.1). In other words, the rollback process searches for the path that links all the transactions while trying to visit as many locations in the transactions as possible. Therefore, the proposed algorithm is meant to search for the longest possible path.

The edges that cross multiple levels of the graph (step 1.4) are used by the algorithm to escape or avoid the transactions that do not connect with their consecutive transactions. However, as they skip transactions, their weights are assigned negative numbers so that they become biased and tend not to be chosen by the algorithm. This results in the longest path that follows the real transactions as much as possible. The idea is proven by Theorem 2 showing that when all transactions are linked together (i.e. when they all represent actual movements), the longest path does not contain multi-level crossing edges.

Theorem 2: Algorithm accuracy. Given a directed graph *G(V, E)* constructed according to the inventory rollback algorithm with *N* levels. Let *V* be a set of nodes and *E* a set of edges. If there is a path passing through all levels of the graph, the longest path does not contain any multi-level crossing edges.

Proof: The shortest path that goes through t levels of G without using multi-level crossing edges requires at least $t-1$ edges. Also, in order for G to have a multi-level crossing edge, G needs to have at least three levels. Suppose the longest path, p, of G contains an edge crossing from level i to level j, where $j-i \geq 2$. The maximum number of edges included in p, except the multi-level crossing one, is two edges, if on level i the path starts from the right node (i.e. one from the origin level and the other from the destination level), and one edge, if on level i the path starts from the left node (i.e. from the destination level). Thus, the minimum length summation of these three edges is equal to -1 (i.e. -2 + 1) for the former case, and 0 (i.e. -1 + 1) for the latter case. However, without using the multi-level crossing edge, moving from level i to level j requires at least $j-i+1$ edges for the former case, and $j-i$ for the latter case. Consequently, the maximum length summation is $i-j-1$ for the former case, and $i-j$ for the latter case. The highest possible value of $i-j$ is -2 (i.e. crossing one edge), which is smaller than -1. Therefore, p is not the longest path of G, which contradicts the assumption. Note the longest path of weight inverse graphs is the one that hold the most negative weight summation. ■

In terms of the computational complexity, constructing a graph for a pallet in step 1 requires $O(V^2)$ node comparisons. The computational complexity required to solve the shortest path problem in step 3 depends on which shortest path algorithm is selected. For example, the Bellman-Ford algorithm requires $O(VE)$ while the DAG-shortest path algorithm using a topological sort requires $O(V+E)$. Traversing through the graph (i.e. step 2 and 4) can be done in linear time. In addition, the rollback algorithm needs to be executed N times, where N is the number of pallets. Therefore, the overall rollback process can be done in polynomial time (i.e. $O(NV^2)$ to $O(NV^3)$).

Although Theorem 2 guarantees that the algorithm always traverses through the graph without using multi-level crossing edges if locations in the transaction follow their chronological order of when they were visited by a pallet, it does not guarantee that the longest path of the case where error transactions (i.e. not executed) occur will be the same as the actual operations, due to the concept of Garbage-In-Garbage-Out. In order to observe how well the algorithm performs when non-executed transactions occur, real pallet moving transaction data gathered from an actual manufacturer is used in Section 3.3. The results are compared with the real inventory snapshots captured once each month by the manufacturer.

3.3 Computational Experiment

In this section, the algorithm is tested with real industrial data in order to evaluate its performance by comparing the rollback inventory to the actual counts provided by the industrial partner. The results are shown in section 3.3.3, followed by a discussion.

3.3.1 Data and environment

The data used to test the algorithm was obtained through a collaboration between MU CELDi and a large chemical manufacturer who produces and supplies agricultural chemicals to the US and global markets. The data includes 13-months of pallet movement transactions for 1,470 materials. The materials are separated into four major types: finished goods, packaging materials, raw materials and semi-finished goods. The statistical detail of the pallet movement transaction data is summarized in Table 3.2. In addition to the pallet movement transactions, the current inventory was retrieved and a snapshot of past inventory counts for every mid-month was also provided.

Table 3.2 Statistical information of the tested data

Number of Transactions	557,296
Number of materials	1,470
Number of pallets	128,027
Average number of transactions per pallets	4
Max number of transactions per pallets	52
Min number of transactions per pallets	1

Each pallet has a unique identifier number to differentiate it from other pallets. The numbers were recorded in the movement transactions along with the origin and destination locations where the pallets were moved from/to. Each transaction was recorded with a date and timestamp. According to the data, some pallets can be split to create a new pallet or added to other pre-existing ones. A new pallet can be created either from another pallet, by the production plant, or being received from suppliers. If a pallet is received into the facility, the origin location of the movement is shown as “RCPT” in the transaction. Conversely, if a pallet is shipped out from the facility (maybe to customers), the destination location is shown as “SHIP” in the transaction. During the creation of the rollback graph, “RCPT” and “SHIP” were considered as locations and have designated nodes.

The locations involved in the material flows consist of multiple onsite locations and two offsite locations. All onsite locations are located inside the production site and in close proximity where a forklift can be used to handle pallets between locations. Two offsite locations are located in the same vicinity as the production plant. Each offsite location charges the company for every pallet stored in each period and is responsible for storing, retrieving and transporting pallets to the production plant.

3.3.2 Experimentation

In this study, a past inventory snapshot is not available, but past inventory counts and a current inventory snapshot is available. Therefore, the algorithm was run for any longest path found. The current inventory (i.e. initial inventory) was used to mark a beginning location of each pallet. While traversing through the longest path obtained by the algorithm, the past inventory at each location was reconstructed. The pallets that have their first locations recorded as warehouse are assumed to have been in the warehouse for 365 days, due to the time scope of the dataset is limited to one year. For example, the first movement transaction of pallet A shows that the pallet was moved from a warehouse to a production plant on January 15th, 2010 and there is no other information recorded regarding how the pallet was received into the warehouse (due to the limited time scope of data set). Therefore, the pallet is assumed to have been in the warehouse for 365 days before being moved to the production plant. Even though this assumption may result in an overestimation of the counts, the situation where the creation time of pallets is unknown only happened to the pallets that exist in the warehouse before the observation period began. Also, the number of such pallets was very low, so the final estimation is expected to be minimally affected.

Similar to the pallets with unknown origin of creation, for the pallets whose destination of consumption are unknown and did not appear in the initial inventory (i.e. the current inventory), but their last movements showed that they were stored in one of the warehouses, these pallets are assumed to be shipped out from the warehouses right after their last transaction was recorded.

In addition to the above two assumptions, only three onsite warehouses' inventories (i.e. L-1, L-2 and L-3) are considered in the experiment because the offsite warehouses also carry the items that are not related to the facility of focus. Also, the past inventory counts given for those locations include every item stored offsite, so the past inventory counts for the offsite locations cannot be used to compare with the rollback inventory.

3.3.3 Result

The algorithm required around 30 minutes to solve the problem on a PC laptop with 4 processor cores and 8 GB of RAM. The rollback results are shown in Figure 3.3. To evaluate the performance of the algorithm, the inventories stored in each location (i.e. L-1, L-2 and L-3) on 15th of every month are counted and summarized in Table 3.2 and Figure 3.4 to 3.6. Next to each pallet count in the table, the difference between the actual count and the rollback results are calculated. The negative numbers imply the algorithm underestimates the inventory, while the positive numbers imply that the inventory was overestimated.

Table 3.3 Rollback inventory for each warehouse

Date	Number of Pallets					
	L-1	Diff.	L-2	Diff.	L-3	Diff.
1/15/10	382	-53	1	1	656	62
2/15/10	580	-34	1	1	994	37
3/15/10	781	33	150	23	1,093	25
4/15/10	765	22	313	41	809	-25
5/15/10	838	-45	483	-13	775	-13
6/15/10	866	-109	613	12	839	24
7/15/10	780	-103	1,061	-11	1,245	-7
8/15/10	828	-29	1,035	-38	1,182	-32
9/15/10	685	-64	880	-60	932	-41
10/15/10	841	-114	1,001	-90	1,040	-79
11/15/10	838	-34	888	-28	934	-25
12/15/10	893	-126	1,094	22	1,089	4

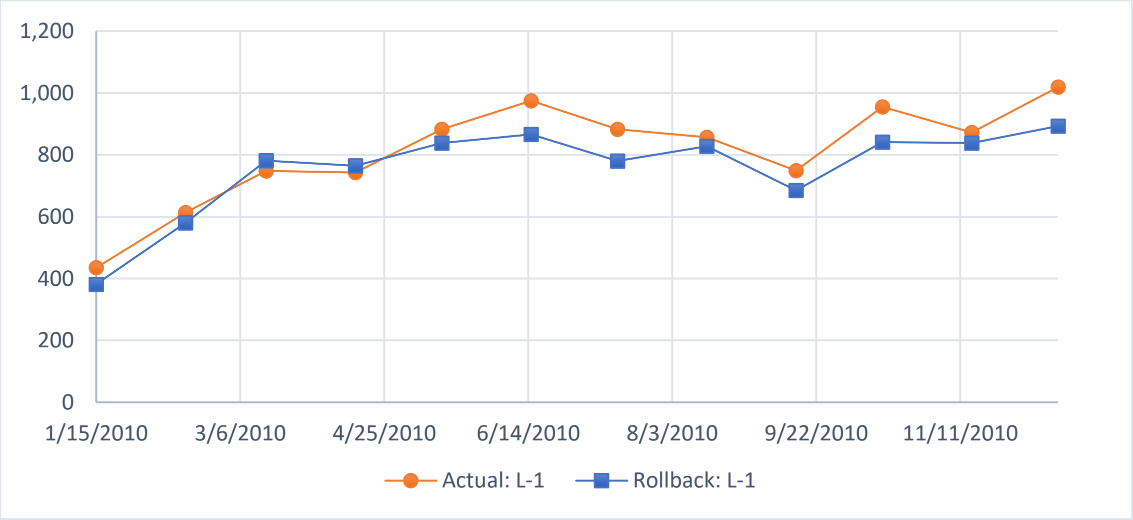

Figure 3.4 Rollback inventory for warehouse 1 (L-1)

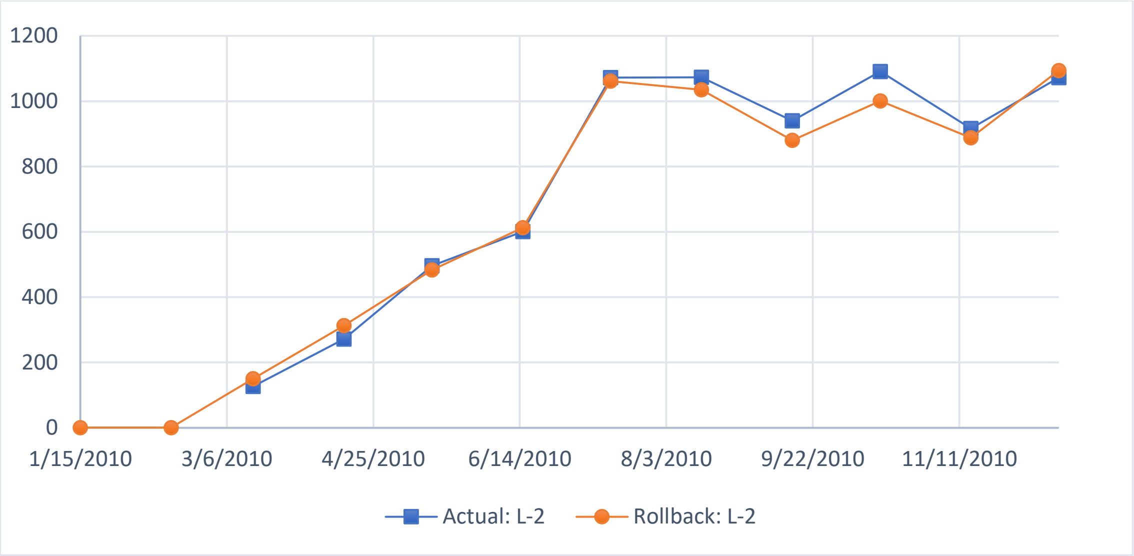

Figure 3.5 Rollback inventory for warehouse 2 (L-2)

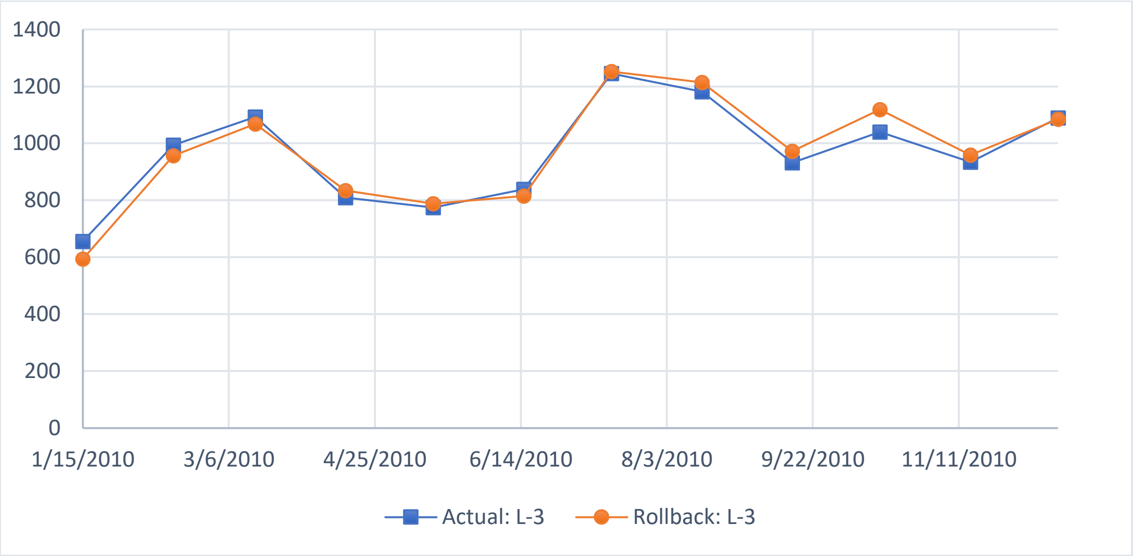

Figure 3.6 Rollback inventory for warehouse 3

As can be seen in Table 3.2, the differences range from one pallet to 126 pallets, which is around 15%. In addition, the weighted-average absolute percentage differences are 8%, 4% and 3% on average for warehouse 1, 2 and 3, respectively. Analysis of Figures 3.4, 3.5, and 3.6 shows that the rollback algorithm seems to work relatively well in reconstructing the past inventory. The rollback inventory establishes the same trend as the actual counts. The overestimation and underestimation are suspected to stem from the disconnected transactions discussed in section 3.1. The disconnection between two consecutive transactions causes the algorithm to choose whether to jump over to other transactions by using multi-level crossing links. This might cause an error, especially when the transaction that the algorithm jumped to does not represent an actual pallet movement. However, this is to be expected. When the data contains a high level of noise, the necessary link information between transactions is likely to be lost. The proposed algorithm seeks to capture as many transaction relationships and locations that appear in the transactions as possible.

3.4 Summary and Conclusions

In this chapter, a polynomial time algorithm to estimate the past inventory stored at each storage location is proposed. The method reconstructs the past inventory by following the longest path that links each pallet movement transaction together. The result of this algorithm could be used to analyze the warehouse or storage utilization when past inventory data is not available. In addition, the performance of the algorithm was evaluated with real industrial data. The results show that the reconstructed inventory stored in each location appears to be close to the actual inventory counts with the biggest difference being 126 pallets in one location (15%), and 5% percentage difference between the rollbacked quantities and actual counts on average among three warehouses.

CHAPTER 4

MATERIAL LOCATION SELECTION MODELS FOR ONSITE AND THIRD-PARTY WAREHOUSES

4.1 Introduction

In this chapter, the material location selection for the two-warehouse problem is introduced. The problem consists of one production plant, one owned warehouse and one third-party warehouse, which is rented through a third-party logistic provider (3PL). The rented warehouse is located outside the production site and, as such, is denoted as an offsite warehouse. The offsite warehouse is typically located in close proximity to the production site, so that the items can be transferred to the onsite locations upon request with minimum lead time. Both warehouses supply raw materials to the production plant and serve as intermediate storage locations for finished goods before being shipped to distribution centers or customers. The onsite warehouse has a limited capacity, in contrast to the offsite warehouse where the 3PL is responsible for preparing storage space as requested by the manufacturer. The goal of the approach presented in this chapter is to effectively utilize the onsite storage by allocating each item or material to one or both of these warehouses over multiple planning periods. The problem aims to minimize the total storage rental and transportation cost which are charged by the 3PL warehousing company for each item stored offsite and each item transferred between offsite and onsite locations. An *item* denotes an individual item flowing in the system, while a *material* denotes a class or type of items in the production system.

Based on the literature review in Chapter 2, relatively few studies address the use of the offsite warehouse together with an onsite warehouse. Those that do address this topic are in the area of inventory control modeling, which searches for an optimal item-procurement policy that minimize either or both storage rental and transportation cost (e.g. Zhou and Yang, 2005; Maiti et al., 2006; Chung et al., 2009; Lee and Hsu, 2009; Bhunia, 2011; Ghiami et al., 2013). However, this kind of problem implicitly assumes that the offsite warehouse acts as an extension part of the onsite warehouse, but with unlimited capacity. The excess inventory that cannot be stored onsite is stored offsite instead. In addition, the onsite warehouse is assumed to be filled first before the offsite warehouse, but the onsite inventory is either consumed after, or repeatedly replenished by the offsite inventory. In this context, the inventory control does not focus on allocating materials to the warehouses. Also, the traditional inventory models consider a procurement policy for each material individually while the research on multi-material inventory models assumes that every material has a limit on the usage of the owned storage capacity or the list of materials stored offsite is identical or a subset list of materials stored onsite.

The other research areas that consider or have multiple storage areas or warehouses as components in their problems include the forward-reserve problem, supply-chain network design and the multi-level storage tool switching problem. Although they use multiple storage locations, the problems do not deal with selecting locations for materials in the two-warehouse production environment. The forward-reserve problem deals with the internal function of storage area that separates the area into forward and reserve. Each has different functionality; in particular, one is used for small size and fast moving items, and the other one is used for bulk-size and slow moving items. Although the problem uses multiple storage areas, they are not identical with different functionalities and typically are part of an internal warehouse configuration; for example, lower-level rack shelves are used as forward area and upper-level rack shelves are used as reserve area. Second, the supply-chain network design focuses on the flow of items moving upstream to downstream to serve demands in the supply-chain network (e.g. Beamon, 1998; Jayaraman and Ross, 2008; Sadjady and Davoudpour, 2012; Shankar et al., 2013). In addition to the first two problems related to inventory control, the concept of multiple storage areas is found in the tool switching problem that arranges and allocates tools into the tool magazine of a machine for efficient access (Matzliach and Tzur, 2000; Hirvikorpi et al., 2006; Carma et al., 2007). As the name implies, the problem deals with arrangement of non-perishable items like tools and focuses on improving the productivity of a machine. It does not address warehouses and inventory issues.

In contrast to the literature, the material location selection problem presented in this research considers that both warehouses are identical and work in conjunction to serve the production plant. That is, some materials can appear in either or both locations and can flow between any location, while production can request items from both locations directly. The proposed models seek to minimize the transportation cost of moving items between onsite and offsite storage, and storage cost. The inbound shipment schedule and outbound shipment schedule are assumed to be given or known to the warehouse manager. Each material is purchased from one supplier. Material transportation between the production site and offsite warehouse, and outgoing shipments are handled by a 3PL provider. An item refers to a pallet and consumes the same unit amount of floor space as other items. However, without loss of generality, the proposed models can be easily modified to account for different pallet sizes by having their sizes characterized as a parameter.

Since the existing information on this topic is limited, based on an actual manufacturer's data, this chapter determines the cost saving opportunity that may be gained from correctly selecting locations for each material. Five different models are proposed for material-location selection with two warehouses, in order to cover different industrial situations or scenarios. The models are varied by the level of decision restrictions and material selection criteria. The five levels are termed: item level, item shipment level, material shipment level, material level and hybrid material level. These five models attempt to answers the following questions:

1. Where to store each material in each time period?
2. Where to receive each material delivered by suppliers in each time period?

As mentioned in Chapter 3, the data used to test the model was gathered through a project in collaboration between the Center for Excellence in Logistics and Distribution at University of Missouri (MU CELDi) and a chemical manufacturing partner. The raw data including an initial inventory and pallet movement transactions was processed by the inventory rollback algorithm introduced in Chapter 3, in order to get the historical inventory information.

The remainder of this chapter is organized as follows. In section 4.2, the models are formulated. Each model is described within its designated section (4.2.2 – 4.2.6). The lists of common parameters and variables that are used by all five models are listed in section 4.2.1. Additional variables that are specifically associated with each model are described in each modeling section. The models and their computational complexities are discussed in sections 4.3 and 4.4, respectively. The computational experiment description and associated results are given in sections 4.5 and 4.6, respectively. Finally, the chapter is summarized in section 4.7.

4.2 Mathematical Models

Five models are formulated in this section. Each model has different operational restrictions in order to represent different material-flow environments. The restrictions are summarized as follows:

1. *Item level model* optimizes the overall material flows by considering movements and shipments of each item individually (Figure 4.1).
2. *Item shipment level model* consolidates shipments delivered by the same supplier for delivery at one location (Figure 4.2).
3. *Material shipment level model* classifies each material to be either an onsite material or an offsite material. All items of the onsite materials are received onsite; otherwise, they are received offsite (Figure 4.3).
4. *Material level model* stores all items of the same material in the material's classified location (Figure 4.4).
5. Instead of having all items of the same material stored in the same location, the *hybrid material level model* specifies an onsite capacity usage limit for each onsite material. In addition, the onsite storage is replenished by the offsite storage in a continuous release pattern (Figure 4.5).

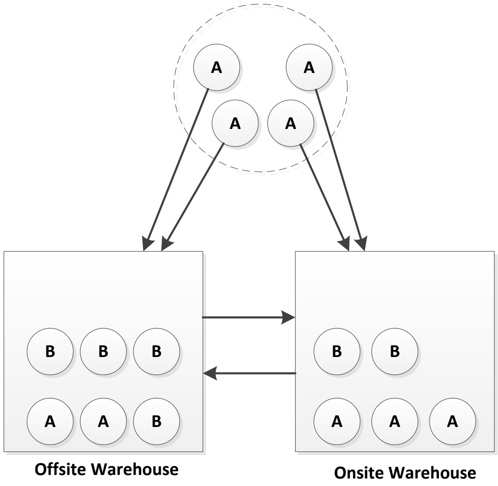

Figure 4.1 Item Level

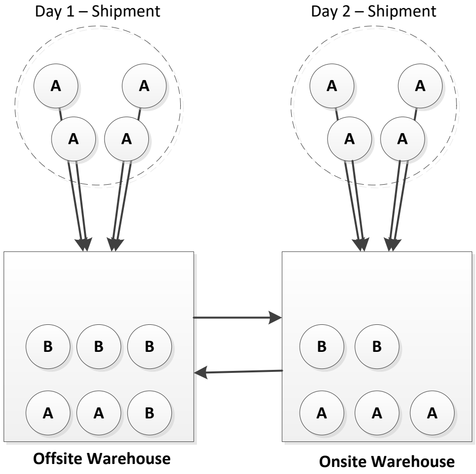

Figure 4.2 Item Shipment Level

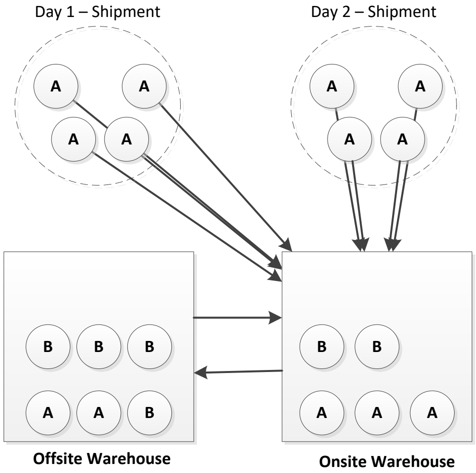

Figure 4.3 Material Shipment Level

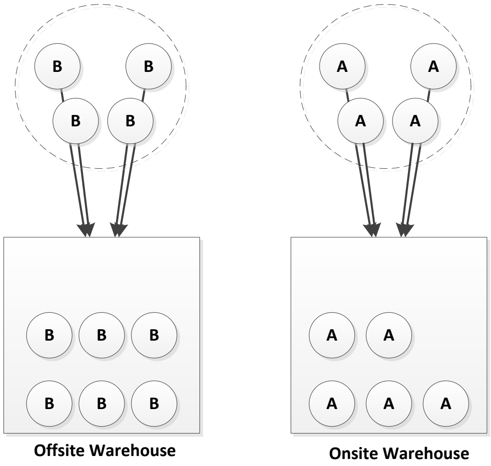

Figure 4.4 Material Level

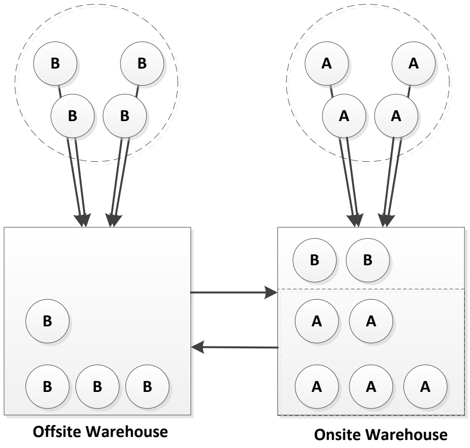

Figure 4.5 Hybrid Material Level

The first two models do not provide a material-location policy, but they are used to optimize the material flows in each time period according to the current information available. They are also used to show a cost saving opportunity if the onsite-space is utilized effectively. The last three models generate material-location policies that classify each material as either an onsite or offsite material. The storage location and item receiving location of each material are defined according to their classes.

4.2.1 Parameters and Variables Notation

The parameters and decision variables included in all five models are given as follows.

Sets:

$\mathcal{I}$: set of items;

$\mathcal{T}$: set of time periods (i.e. 1, 2, 3, …, $|\mathcal{T}|$);

K_t: set of the shipments delivered in period t;

Parameters:

P_{it}: production demand quantity of item i in period t;

Q_{it}^{on}: number of item i stored onsite in period t;

Q_{it}^{off}: number of item i stored offsite in period t;

Q_{i0}^{on}: initial number of item i stored onsite;

Q_{i0}^{off}: initial number of item i stored offsite;

G_{it}: quantity of item i moved out from production plant in period t;

V_{it}: inbound quantity of item i received in period t;

W_{it}: outbound quantity of item i shipped in period t;

C: capacity of the onsite warehouse;

M: large constant number;

R: rented storage cost per pallet;

T: transportation cost per pallet;

Decision variables:

τ_{it}^{on}: number of items i moved from onsite storage to offsite storage in period t;

τ_{it}^{off}: number of items i moved from onsite storage to offsite storage in period t;

ρ_{it}^{on}: number of items i moved from onsite storage to production plant in period t;

ρ_{it}^{off}: number of items i moved from offsite storage to production plant in period t;

q_{it}^{on}: number of items i stored onsite at the end of period t;

q_{it}^{off}: number of items i stored offsite at the end of period t;

q_{i0}^{on}: initial number of items i stored onsite;

q_{i0}^{off}: initial number of items i stored offsite;

g_{it}^{on}: number of items i moved from production plant to onsite storage in period t.

g_{it}^{off}: number of items i moved from production plant to offsite storage in period t.

w_{it}^{on}: number of outgoing items i shipped from the onsite storage in period t;

w_{it}^{on}: number of outgoing items i shipped from the offsite storage in period t;

4.2.2 Item Level Model

The item level model individually assigns each item, including new arrivals, to a location, which is either one of the warehouses or the production plant. In addition to the parameters and variables presented in section 4.2.1, the item level model introduces additional variables as follows:

v_{it}^{on}: number of item *i* received onsite in period *t*.

v_{it}^{off}: number of item *i* received offsite in period *t*.

The model is formulated as:

The objective function (4.1) minimizes the total cost incurred by shipments moving among the onsite locations and offsite location, and the storage rental for each item stored in the offsite warehouse. The transportation cost and storage rental are charged by the 3PL company for each item transferred between onsite locations at the end of each time period. The shipments charged by the 3PL company include the flows between the two warehouses (τ_{it}^{on} and τ_{it}^{off}), and between the offsite warehouse and the production plant (ρ_{it}^{off} and g_{it}^{off}).

$MIN\ Total\ Cost$:

$$\sum_{i\in\mathcal{I}}\sum_{t\in\mathcal{T}}\left(\tau_{it}^{off}+\tau_{it}^{on}+\rho_{it}^{off}+g_{it}^{off}\right)*T\ +\ \sum_{i\in\mathcal{I}}\sum_{t\in\mathcal{T}}q_{it}^{off}*R \tag{4.1}$$

$Subject\ to$:

$$q_{it}^{on}=\ q_{i(t-1)}^{on}+v_{it}^{on}-\tau_{it}^{on}+\tau_{it}^{off}+g_{it}^{on}-\rho_{it}^{on}-w_{it}^{on} \qquad \forall i\in\boldsymbol{\mathcal{I}},t\in\boldsymbol{\mathcal{T}} \tag{4.2}$$

$$q_{it}^{off}=\ q_{i(t-1)}^{off}+v_{it}^{off}-\tau_{it}^{off}+\tau_{it}^{on}+g_{it}^{off}-\rho_{it}^{off}-w_{it}^{off} \qquad \forall i\in\boldsymbol{\mathcal{I}},t\in\boldsymbol{\mathcal{T}} \tag{4.3}$$

$$\sum_{i\in\boldsymbol{\mathcal{I}}}q_{it}^{on}\le C \qquad \forall t\in\boldsymbol{\mathcal{T}}+\{\mathbf{0}\} \tag{4.4}$$

$$V_{it}^{off}+V_{it}^{on}\ =\ v_{it}^{off}+v_{it}^{on} \qquad \forall i\in\boldsymbol{\mathcal{I}},t\in\boldsymbol{\mathcal{T}} \tag{4.5}$$

$$P_{it}^{off}+P_{it}^{on}\ =\ \rho_{it}^{off}+\rho_{it}^{on} \qquad \forall i\in\boldsymbol{\mathcal{I}},t\in\boldsymbol{\mathcal{T}} \tag{4.6}$$

$$W_{it}^{off}+W_{it}^{on}=w_{it}^{off}+w_{it}^{on} \qquad \forall i\in\boldsymbol{\mathcal{I}},t\in\boldsymbol{\mathcal{T}} \tag{4.7}$$

$$G_{it}^{off}+G_{it}^{on}=g_{it}^{off}+g_{it}^{on} \qquad \forall i\in\boldsymbol{\mathcal{I}},t\in\boldsymbol{\mathcal{T}} \tag{4.8}$$

$$q_{i0}^{off}+\ q_{i0}^{on}\ge Q_{i0}^{off}+\ Q_{i0}^{on} \qquad \forall i\in\boldsymbol{\mathcal{I}} \tag{4.9}$$

$$q_{it}^{off},q_{it}^{on},\rho_{it}^{off},\rho_{it}^{on},\tau_{it}^{off},\tau_{it}^{on},w_{it}^{off},w_{it}^{on},g_{it}^{off},g_{it}^{on}\ge 0 \qquad \forall i\in\boldsymbol{\mathcal{I}},t\in\boldsymbol{\mathcal{T}} \tag{4.10}$$

Constraints (4.2) and (4.3) balance the onsite and offsite inventories according to their inflow and outflow. The incoming shipments of each material can be split and received at multiple locations (v_{it}^{on} and v_{it}^{off}). Constraint (4.4) limits the usage of the onsite warehouse in each time period to its capacity. Constraints (4.5) – (4.8) ensures all of the item quantities that are scheduled to be received, consumed by the production plant, shipped out to serve demands, and produced by the production plant in each period are met, respectively. Constraint (4.9) ensures that the total initial inventory does not exceed the actual amount recorded. Last but not least, constraint (4.10) guarantees non-negative values to be assigned to the variables.

As each item is handled individually, this model does not generate a material-location policy. In the other words, it does not answer one of the two main questions (goals) presented in section 4.1 concerning where to store each material item and where to receive each material item. However, this model is used to explore an opportunity for cost reduction in both transportation and storage by efficiently utilizing the available resources such as owned storage space, forklifts and labors. That is, the results of this model serve as a lower bound to other subsequent models. In addition, it serves as a foundation for the subsequent models and the one presented in Chapter 5.

4.2.3 Item Shipment Level Model

The item shipment level consolidates the item shipments purchased from the same supplier so they are received at one location, in order to reduce the number of inbound shipments that need to be monitored and to avoid the chance of being charged by the suppliers or shipment carriers for multiple shipments or order splits. This model decides on the receiving location for each shipment delivered in each time period. It allows the warehouse manager to dynamically make decisions on where to receive the inbound shipments according to the most current information.

Since the model must decide where to receive each shipment delivered from a supplier, another binary decision variable is introduced.

y_{it} : binary variable equal to 1 if the shipment of material *i* delivered at time *t* is received onsite, and 0 otherwise.

The item shipment level model can be formulated as follows.

$MIN\ Total\ Cost$:

$$\sum_{i\in\mathcal{I}}\sum_{t\in\mathcal{T}}\left(\tau_{it}^{off}+\tau_{it}^{on}+\rho_{it}^{off}+g_{it}^{off}\right)*T\ +\ \sum_{i\in\mathcal{I}}\sum_{t\in\mathcal{T}}q_{it}^{off}*R \qquad (4.11)$$

$Subject\ to$:

$$q_{it}^{on}=\ q_{i(t-1)}^{on}+\mathrm{y}_{it}V_{it}-\tau_{it}^{on}+\tau_{it}^{off}+g_{it}^{on}-\rho_{it}^{on}-w_{it}^{on} \qquad \forall i\in\mathcal{I},t\in\mathcal{T} \quad (4.12)$$

$$q_{it}^{off}=\ q_{i(t-1)}^{off}+(1-\mathrm{y}_{it})V_{it}-\tau_{it}^{off}+\tau_{it}^{on}+g_{it}^{off}-\rho_{it}^{off}-w_{it}^{off} \qquad \forall i\in\mathcal{I},t\in\mathcal{T} \quad (4.13)$$

$$\sum_{i\in\mathcal{I}}q_{it}^{on}\ \le C \qquad \forall t\in\mathcal{T}+\{\mathbf{0}\} \quad (4.14)$$

$$V_{it}^{off}+V_{it}^{on}\ =\ v_{it}^{off}+v_{it}^{on} \qquad \forall i\in\mathcal{I},t\in\mathcal{T} \quad (4.15)$$

$$P_{it}^{off}+P_{it}^{on}\ =\ \rho_{it}^{off}+\rho_{it}^{on} \qquad \forall i\in\mathcal{I},t\in\mathcal{T} \quad (4.16)$$

$$W_{it}^{off}+W_{it}^{on}=w_{it}^{off}+w_{it}^{on} \qquad \forall i\in\mathcal{I},t\in\mathcal{T} \quad (4.17)$$

$$G_{it}^{off}+G_{it}^{on}=g_{it}^{off}+g_{it}^{on} \qquad \forall i\in\mathcal{I},t\in\mathcal{T} \quad (4.18)$$

$$q_{i0}^{off}+\ q_{i0}^{on}\ge Q_{i0}^{off}+\ Q_{i0}^{on} \qquad \forall i\in\mathcal{I} \quad (4.19)$$

$$q_{it}^{off},q_{it}^{on},\rho_{it}^{off},\rho_{it}^{on},\tau_{it}^{off},\tau_{it}^{on},w_{it}^{off},w_{it}^{on},g_{it}^{off},g_{it}^{on}\ge 0 \qquad \forall i\in\mathcal{I},t\in\mathcal{T} \quad (4.20)$$

$$y_{it} \in \{0,1\} \qquad \forall i \in \mathcal{I}, t \in \mathcal{T} \quad (4.21)$$

Similar to the previous model, the objective function (4.11) minimizes the transportation cost and storage rental charged by the 3PL company. Constraints (4.12) - (4.13) balance the item flows that move in-and-out of each location. Different from the item level model, the shipments delivered to the production site are consolidated and scheduled to be received either onsite or offsite. Constraint (4.14) limits the maximum amount of items stored in the onsite warehouse to the warehouse capacity. Constraints (4.15) – (4.18) ensures all of the item quantities that are scheduled to be received, consumed by the production plant, shipped out to serve demands, and produced by the production plant in each period are met, respectively. Constraint (4.19) ensures that the total initial inventory does not exceed the actual amount recorded. Constraint (4.20) ensures that only nonnegative numbers are assigned to the shipment flows while constraint (4.21) confines the values of decision variable y_{it} to either one or zero.

Similar to the previous model, the item shipment model does not fully establish a material-location policy. Instead, it simulates the case where the warehouse manager decides periodically where to receive each material shipment, according to the information available.

4.2.4 Material Shipment Level Model

The material shipment level model categorizes each material as either onsite or offsite material. The onsite material items, after leaving the supplier locations, will be delivered onsite, and vice versa for offsite materials.

To categorize each material, an additional variable is introduced.

x_i : binary decision variable equal to 1 if material i is an onsite material, and 0 otherwise.

The material shipment level model is formulated as follows.

$MIN\ Total\ Cost$:

$$\sum_{i\in\boldsymbol{\mathcal{I}}}\sum_{t\in\boldsymbol{\mathcal{T}}}\left(\tau_{it}^{off}+\tau_{it}^{on}+\rho_{it}^{off}+g_{it}^{off}\right)*T\ +\ \sum_{i\in\boldsymbol{\mathcal{I}}}\sum_{t\in\boldsymbol{\mathcal{T}}}q_{it}^{off}*R \qquad (4.22)$$

$Subject\ to$:

$$q_{it}^{on}=\ q_{i(t-1)}^{on}+\mathrm{x}_iV_{it}-\tau_{it}^{on}+\tau_{it}^{off}+g_{it}^{on}-\rho_{it}^{on}-w_{it}^{on} \qquad \forall i\in\boldsymbol{\mathcal{I}},t\in\boldsymbol{\mathcal{T}} \qquad (4.23)$$

$$q_{it}^{off}=\ q_{i(t-1)}^{off}+(1-\mathrm{x}_i)V_{it}-\tau_{it}^{off}+\tau_{it}^{on}+g_{it}^{off}-\rho_{it}^{off}-w_{it}^{off} \qquad \forall i\in\boldsymbol{\mathcal{I}},t\in\boldsymbol{\mathcal{T}} \qquad (4.24)$$

$$\sum_{i\in\boldsymbol{\mathcal{I}}}q_{it}^{on}\leq C \qquad \forall t\in\boldsymbol{\mathcal{T}}+\{\mathbf{0}\} \qquad (4.25)$$

$$V_{it}^{off}+V_{it}^{on}\ =\ v_{it}^{off}+v_{it}^{on} \qquad \forall i\in\boldsymbol{\mathcal{I}},t\in\boldsymbol{\mathcal{T}} \qquad (4.26)$$

$$P_{it}^{off}+P_{it}^{on}\ =\ \rho_{it}^{off}+\rho_{it}^{on} \qquad \forall i\in\boldsymbol{\mathcal{I}},t\in\boldsymbol{\mathcal{T}} \qquad (4.27)$$

$$W_{it}^{off}+W_{it}^{on}=w_{it}^{off}+w_{it}^{on} \qquad \forall i\in\boldsymbol{\mathcal{I}},t\in\boldsymbol{\mathcal{T}} \qquad (4.28)$$

$$G_{it}^{off}+G_{it}^{on}=g_{it}^{off}+g_{it}^{on} \qquad \forall i\in\boldsymbol{\mathcal{I}},t\in\boldsymbol{\mathcal{T}} \qquad (4.29)$$

$$q_{i0}^{off}+\ q_{i0}^{on}\geq Q_{i0}^{off}+\ Q_{i0}^{on} \qquad \forall i\in\boldsymbol{\mathcal{I}} \qquad (4.30)$$

$$q_{it}^{off},q_{it}^{on},\rho_{it}^{off},\rho_{it}^{on},\tau_{it}^{off},\tau_{it}^{on},w_{it}^{off},w_{it}^{on},g_{it}^{off},g_{it}^{on}\geq 0 \qquad \forall i\in\boldsymbol{\mathcal{I}},t\in\boldsymbol{\mathcal{T}} \qquad (4.31)$$

$$x_i\in\ \{0,1\} \qquad \forall i\in\boldsymbol{\mathcal{I}},t\in\boldsymbol{\mathcal{T}} \qquad (4.32)$$

The objective function and all constraints remain the same as the item level model, except the inventory balance constraint (4.23) and (4.24), and binary constraint (4.32). Instead of deciding a receiving location for each shipment, the model decides a receiving location for each material. Thus, a binary variable x_i is used in (4.23), (4.24) and (4.32), instead of y_{it}.

4.2.5 Material Level Model

Similar to the material shipment level model, the material level model categorizes each material as either onsite or offsite material. Each material is received at one location. In contrast to the previous model, items of the same material are also stored in one location, either onsite or offsite.

To categorize each material, another binary decision is required.

x_i : binary decision variable equal to 1 if material *i* is an onsite material, and 0 otherwise.

The material level model can then be formulated as follows.

$MIN\ Total\ Cost$:

$$\sum_{i\in\mathcal{I}}\sum_{t\in\mathcal{T}}\left(\tau_{it}^{off}+\tau_{it}^{on}+\rho_{it}^{off}+g_{it}^{off}\right)*T\ +\ \sum_{i\in\mathcal{I}}\sum_{t\in\mathcal{T}}q_{it}^{off}*R \qquad (4.33)$$

$Subject\ to$:

$$q_{it}^{on} = q_{i(t-1)}^{on} + \mathrm{x}_i V_{it} - \tau_{it}^{on} + \tau_{it}^{off} + g_{it}^{on} - \rho_{it}^{on} - w_{it}^{on} \qquad \forall i \in \mathcal{I}, t \in \mathcal{T} \qquad (4.34)$$

$$q_{it}^{off} = q_{i(t-1)}^{off} + (1-\mathrm{x}_i)V_{it} - \tau_{it}^{off} + \tau_{it}^{on} + g_{it}^{off} - \rho_{it}^{off} - w_{it}^{off} \qquad \forall i \in \mathcal{I}, t \in \mathcal{T} \qquad (4.35)$$

$$\sum_{i\in\mathcal{I}} q_{it}^{on} \leq C \qquad \forall t \in \mathcal{T} + \{\mathbf{0}\} \qquad (4.36)$$

$$V_{it}^{off} + V_{it}^{on} = v_{it}^{off} + v_{it}^{on} \qquad \forall i \in \mathcal{I}, t \in \mathcal{T} \qquad (4.37)$$

$$P_{it}^{off} + P_{it}^{on} = \rho_{it}^{off} + \rho_{it}^{on} \qquad \forall i \in \mathcal{I}, t \in \mathcal{T} \qquad (4.38)$$

$$W_{it}^{off} + W_{it}^{on} = w_{it}^{off} + w_{it}^{on} \qquad \forall i \in \boldsymbol{\mathcal{I}}, t \in \boldsymbol{\mathcal{T}} \tag{4.39}$$

$$G_{it}^{off} + G_{it}^{on} = g_{it}^{off} + g_{it}^{on} \qquad \forall i \in \boldsymbol{\mathcal{I}}, t \in \boldsymbol{\mathcal{T}} \tag{4.40}$$

$$q_{i0}^{off} + q_{i0}^{on} \geq Q_{i0}^{off} + Q_{i0}^{on} \qquad \forall i \in \boldsymbol{\mathcal{I}} \tag{4.41}$$

$$q_{it}^{on} \leq x_i \cdot M \qquad \forall i \in \boldsymbol{\mathcal{I}}, t \in \boldsymbol{\mathcal{T}} \tag{4.42}$$

$$q_{it}^{off} \leq (1 - x_i)M \qquad \forall i \in \boldsymbol{\mathcal{I}}, t \in \boldsymbol{\mathcal{T}} \tag{4.43}$$

$$q_{it}^{off}, q_{it}^{on}, \rho_{it}^{off}, \rho_{it}^{on}, \tau_{it}^{off}, \tau_{it}^{on}, w_{it}^{off}, w_{it}^{on}, g_{it}^{off}, g_{it}^{on} \geq 0 \qquad \forall i \in \boldsymbol{\mathcal{I}}, t \in \boldsymbol{\mathcal{T}} \tag{4.44}$$

$$x_i \in \{0,1\} \qquad \forall i \in \boldsymbol{\mathcal{I}}, t \in \boldsymbol{\mathcal{T}} \tag{4.45}$$

In addition to the constraints that appear in the material level model, two more constraints are added. Constraints (4.39) and (4.40) ensure that all onsite materials are stored onsite, and all offsite materials are stored offsite.

4.2.6 Hybrid Material Level Model

While the material shipment level model determines an item receiving location for each material and allows the warehouse manager to decide where and how they should move the items after implementing the method (policy), the material level model provides the warehouse manager the storage policy that strictly store items of the same material in one location. However, the material level policy may not fully utilize the onsite space, as the onsite inventory level may change after implementing the policy. In addition, some fast-moving materials (i.e. highly consumed materials) may not be stored close to the point of use (i.e. the production plant) if they consume a lot of space, compared to the onsite warehouse capacity. The hybrid material level model seeks to capture the advantages of both models by specifying a space usage limit for each material stored onsite. In other words, each onsite material is allowed to consume the onsite storage up to the limit specified by the model, and then the remaining quantity will be stored offsite. In addition, once the onsite space becomes available, the onsite material will be replenished up to the limit, in order to maintain the onsite materials onsite. This concept is similar to the assumption given in the literature concerning two warehouse inventory models, in which the onsite storage is replenished by the offsite storage. Even though items of the same material might be split over different locations, the replenishment criteria will attempt to keep them together in one location, and also allow the warehouse managers to maintain an inventory rotation structure (e.g. first-in-first-out).

In order to categorize each material and determine the limit for each onsite material, additional variables are introduced.

x_i : binary decision variable equal to 1 if material i is an onsite material, and 0 otherwise.

r_{it} : binary decision variable equal to 1 if there are some pallets of material i stored offsite at time t, and 0 otherwise.

l_i : maximum number of pallets that could be stored onsite for onsite material i

Then, the hybrid material level model can be formulated as follows. The objective function (4.46) and the constraints up to (4.54) are the same as the material level model and material shipment level model. Constraint (4.55) bounds the space-usage of each onsite material by the onsite warehouse capacity, while constraint (4.56) ensures that sum of the onsite space usage is not more than the onsite warehouse capacity. Constraints (4.57) - (4.59) force the model to replenish the onsite material inventories.

$MIN\ Total\ Cost$:

$$\sum_{i\in\boldsymbol{\mathcal{I}}}\sum_{t\in\boldsymbol{\mathcal{T}}}\left(\tau_{it}^{off}+\tau_{it}^{on}+\rho_{it}^{off}+g_{it}^{off}\right)*T\ +\ \sum_{i\in\boldsymbol{\mathcal{I}}}\sum_{t\in\boldsymbol{\mathcal{T}}}q_{it}^{off}*R \qquad (4.46)$$

$Subject\ to$:

$$q_{it}^{on}=\ q_{i(t-1)}^{on}+\mathrm{x}_iV_{it}-\tau_{it}^{on}+\tau_{it}^{off}+g_{it}^{on}-\rho_{it}^{on}-w_{it}^{on} \qquad \forall i\in\boldsymbol{\mathcal{I}},t\in\boldsymbol{\mathcal{T}} \qquad (4.47)$$

$$q_{it}^{off}=\ q_{i(t-1)}^{off}+(1-\mathrm{x}_i)V_{it}-\tau_{it}^{off}+\tau_{it}^{on}+g_{it}^{off}-\rho_{it}^{off}-w_{it}^{off} \qquad \forall i\in\boldsymbol{\mathcal{I}},t\in\boldsymbol{\mathcal{T}} \qquad (4.48)$$

$$\sum_{i\in\boldsymbol{\mathcal{I}}}q_{it}^{on}\le C \qquad \forall t\in\boldsymbol{\mathcal{T}}+\{\mathbf{0}\} \qquad (4.49)$$

$$V_{it}^{off}+V_{it}^{on}\ =\ v_{it}^{off}+v_{it}^{on} \qquad \forall i\in\boldsymbol{\mathcal{I}},t\in\boldsymbol{\mathcal{T}} \qquad (4.50)$$

$$P_{it}^{off}+P_{it}^{on}\ =\ \rho_{it}^{off}+\rho_{it}^{on} \qquad \forall i\in\boldsymbol{\mathcal{I}},t\in\boldsymbol{\mathcal{T}} \qquad (4.51)$$

$$W_{it}^{off}+W_{it}^{on}=w_{it}^{off}+w_{it}^{on} \qquad \forall i\in\boldsymbol{\mathcal{I}},t\in\boldsymbol{\mathcal{T}} \qquad (4.52)$$

$$G_{it}^{off}+G_{it}^{on}=g_{it}^{off}+g_{it}^{on} \qquad \forall i\in\boldsymbol{\mathcal{I}},t\in\boldsymbol{\mathcal{T}} \qquad (4.53)$$

$$q_{i0}^{off}+\ q_{i0}^{on}\ge Q_{i0}^{off}+\ Q_{i0}^{on} \qquad \forall i\in\boldsymbol{\mathcal{I}} \qquad (4.54)$$

$$l_i\ \le\ x_i\cdot C \qquad \forall i\in\boldsymbol{\mathcal{I}} \qquad (4.55)$$

$$\sum_{i\in\boldsymbol{\mathcal{I}}}l_i\ \le\ C \qquad (4.56)$$

$$q_{it}^{on}\ -\ l_i\ \ \le\ \ (1-\ x_i)\cdot M \qquad \forall i\in\boldsymbol{\mathcal{I}},t\in\boldsymbol{\mathcal{T}} \qquad (4.57)$$

$$l_i-\ q_{it}^{on}\ \ \le\ \ (1-\ r_{it})\cdot M \qquad \forall i\in\boldsymbol{\mathcal{I}},t\in\boldsymbol{\mathcal{T}} \qquad (4.58)$$

$$q_{it}^{off}\ \ \le\ \ r_{it}\cdot M \qquad \forall i\in\boldsymbol{\mathcal{I}},t\in\boldsymbol{\mathcal{T}} \qquad (4.59)$$

$$q_{it}^{off}, q_{it}^{on}, \rho_{it}^{off}, \rho_{it}^{on}, \tau_{it}^{off}, \tau_{it}^{on}, w_{it}^{off}, w_{it}^{on}, g_{it}^{off}, g_{it}^{on} \geq 0 \qquad \forall i \in \boldsymbol{\mathcal{I}}, t \in \boldsymbol{\mathcal{T}} \qquad (4.60)$$

$$r_{it}, x_i \in \{0,1\} \qquad \forall i \in \boldsymbol{\mathcal{I}}, t \in \boldsymbol{\mathcal{T}} \qquad (4.61)$$

4.3 Model Discussion

It is important to note that all of the proposed models do not intend to generate material flow plans or to specify how to move each material item, but to generate material-location plans, in order to effectively utilize the available resources that are currently owned by a manufacturer with respect to storage and transportation costs. The material flows calculated by the proposed models, in other words, represent a network of locations. The main goals which the proposed models are trying to achieve are then boiled down to two specific questions. In each time period,

1. Where to receive each material delivered from suppliers?
2. Where to store each material?

The item level model optimizes the material flows of each individual item according to current information such as customer demand, production demand and the item quantities that are produced in each time period. Due to the fact that each item is considered individually, the total cost yielded by this model is expected to be the lowest among the other proposed models. However, in term of the main goals, the model answers neither of the above questions. It does not generate a material-location policy to allocate materials to storage locations, nor specify a receiving location for each shipment delivered to the production site. Each delivered shipment may be split and received at different locations and therefore results in multiple shipments. Having an order or shipment split can cause the manufacturer to lose their economies of scale, especially when the splitting creates multiple less-than-truck-loads (LTLs). In addition, having an order split to multiple locations requires an additional step in the monitoring process to ensure that the order is received completely and properly. Nevertheless, its formulation provides a foundation for developing the other subsequent models, and later will be used in Chapter 5 for deriving a two-warehouse production planning model.

The item shipment level model differs from the item level model in that it determines a receiving location for each delivered shipment. The model is proposed for the system in which an efficient inventory planning and tracking system such as Enterprise Resource Planning (ERP) and RFID is available and also integrated with the rented warehouse, in order to capture both item locations and status (e.g. expiry and receiving date). As some materials delivered have to go through a quality inspection process, separating items of the same material to be delivered separately may require additional inspection units to be installed in both warehouses. Therefore, this policy may be applied to a system that does not require additional installations of material inspection units if a material is received at different locations. In this kind of environment, the shipments or orders delivered may be assigned to different receiving locations with regard to the current information such as current inventory levels, production schedules and realized demands. However, the inventory rotation process may be hindered by the dispersion of the same material items across different locations. To handle such system, the material and material shipment level models are proposed.

Instead of considering each item or shipment individually, the material shipment level model categorizes each material as either onsite or offsite material. Each material is assigned to one delivery location in order to centralize and reduce a number of inspection units, and also to set up a practical rule for receiving each material. In term of real practice, the model only selects a receiving location for each material and relies on the warehouse manager to decide where to store each item or which items need to be moved around. As the storage location is not a major concern by the model, this strategy may be applied to a system that consists of a relatively low number of materials whose items have relatively similar and high consumption rates, or a system with perishable or short-life items such as fresh food or grains. In this kind of environment, we do not expect the items to remain in storage for a long time before being consumed by the production plant.

Even though the material shipment level model attempts to classify each material as either onsite or offsite material, the material locations need to be frequently evaluated, especially in the case that a summation of the onsite material inventories is higher than the onsite capacity. In this case, the warehouse manager is required to make decisions on which of the items that are currently stored onsite, but need to be move offsite, in order to free up space for newly arrived items. Depending on how the decisions are made, items of the same material may be dispersed across different locations; therefore, reducing the item visibility and hindering the stock rotation.

In contrast to the material shipment level, the material level model not only classifies each material, but also collects all items of the same material in one location for item tracking and rotating purposes. In other words, it provides an explicit rule/policy to store items so that workers can easily and instantaneously identify the storage location of each item. The drawback of this method is that the policy may yield lower onsite-space utilization than the other methods, because the inventories of the onsite materials may fluctuate over time (i.e. due to consumption and procurement) while the offsite inventory cannot fill up the empty space in the onsite warehouse. In addition, some of the fast-moving items with the volumes that are too high to be stored entirely onsite have to be stored offsite, leading to multiple item transshipments between storage and production.

While the material shipment level model utilizes all of the onsite space by allowing items to be moved around, the material level model sacrifices space utilization in order to maintain item collectivity and also provide the warehouse manager with ease of maintaining inventory locations. In other words, both of them can be viewed as an extreme case of each other. In order to capture the benefits of both methods, the hybrid material level specifies a storage limit for each onsite material, and requires the onsite materials to be stored onsite with respect to their limits. Even though the method prioritizes the onsite materials over the offsite materials for the onsite storage, it allows some of the offsite materials to be moved into the onsite warehouse if there is available space. The attempt is to increase the onsite warehouse utilization. By continuously replenishing the onsite storage with the onsite items that are stored offsite, the method guarantees that the onsite materials, if any, are always available onsite for quick access. Also, it provides both an explicit material receiving policy and a material storage policy, so that workers can directly determine where to look for each material. In term of the stock rotation process, however, the hybrid material level may not achieve the same level of convenience in terms of stock rotation as the material level, since the method may still keep each onsite material in separate locations. Nevertheless, the rotation process is expected to be improved from the material shipment level, since items can only flow from the offsite warehouse to the onsite warehouse; therefore, enhancing the item sortation.

4.4 Computational Complexity Analysis

As quantities of the items are commonly expressed as integer numbers, the proposed models are integer linear programming (ILP) models due to the nature of the item definition (i.e. pallet). ILPs are commonly known as NP-hard problems, whose level of complexity depends greatly on the number of integer or binary variables. However, in our case, the problem can be depicted as a network flow problem (Figure 4.6). In each time period, a sub-network is constructed of item flows between locations. The network consists of one source that represents suppliers and one sink that represents demand locations. An inbound flow runs from the source to one of the warehouses, and an outbound flow runs from one of the warehouses to the sink. Two consecutive sub-networks are linked by the flows originated from the nodes in the older period to the ones of the same locations in the next period. These interconnected links are captured by the inventory balance constraints. In addition, all of the inventory counts and shipment quantities are integer. Because of this representation, the integrality theory can be applied. Consequently, the item flow variables can be solved as continuous variables. Therefore, the item level model is turned into a linear programing model while the other models, except the hybrid material level model, become binary programming models. That is, for a system with n periods and m materials, the number of integer variables is reduced to $O(nm)$ for the item shipment level model and the hybrid material level model, and $O(m)$ for the material shipment level model and the material level model. Later, the experimentation shows that the models can be solved optimally or with relatively low optimality gap when real industrial data is utilized.

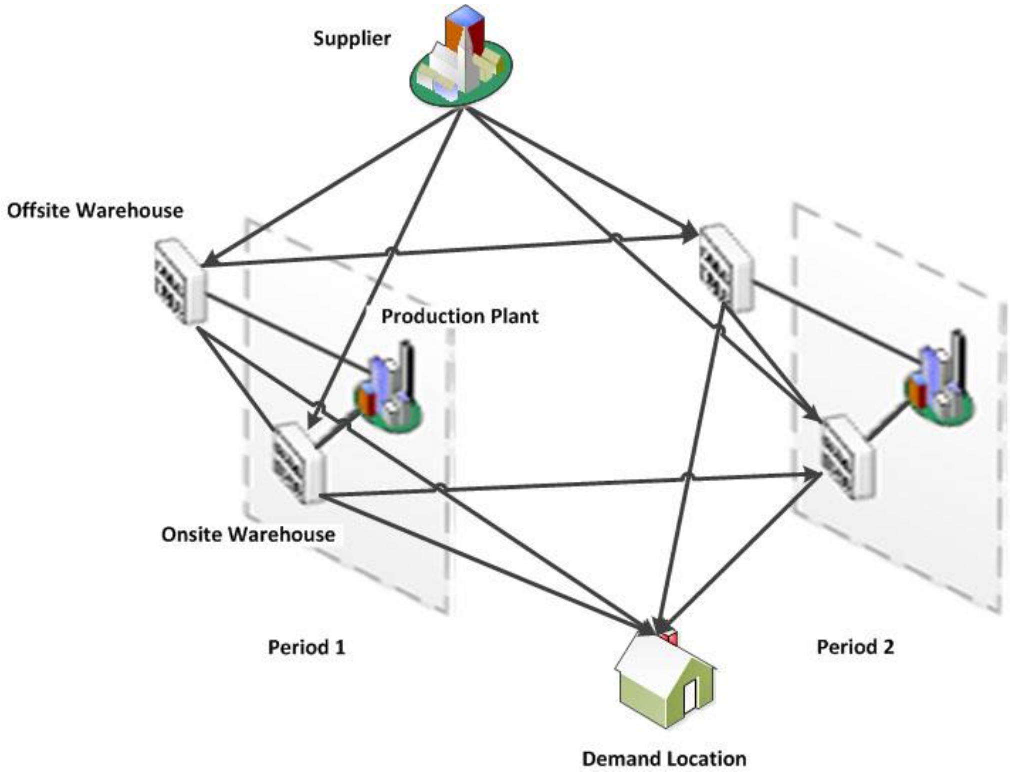

Figure 4.6 Network Flow Representation of the Material Location Selection Models

4.5 Computational Experimentation

4.5.1 Data and Case Study

The data used to evaluate the performance of the five models is based on a chemical manufacturer who produces multiple kinds of chemical products to support global agriculture markets. The manufacturer currently hires a 3PL warehousing company to be responsible for raw materials and finished goods storage. The 3PL company rents a warehouse located outside the production site on behalf of the manufacturer and charges the manufacturer for every pallet stored in the warehouse and for every pallet transferred between the warehouse and the production site. In addition to renting the offsite storage through the 3PL, the manufacturer also owns warehouses that are located at the production site. The onsite warehouses are operated by the manufacturer. Transporting pallets between the onsite warehouses and production plants are done by forklifts. However, the transportation in-and-out the production site is carried by the 3PL.

The production plants consume multiple kinds of raw materials, including packaging materials and produce multiple kinds of finished goods. The materials could be supplied by either onsite or offsite warehouses. The finished goods are temporarily stored in the same warehouses as raw materials before being transported to a separate offsite warehouse (i.e. distribution center) for shipment consolidation.

In addition to the warehouse management team, who is responsible for item storage and supplying materials to the production plants, the manufacturer also has a material procurement team who is responsible for purchasing materials from suppliers. At the time of this research, the manufacturer determines an item receiving location for each material shipment delivered from their suppliers and no explicit material-location rule exist. The purchased quantities of materials and purchasing time are not solely decided according to the production demand, but also the prices that are currently offered by the suppliers. Therefore, materials can be purchased in large quantities that may exceed the owned warehouse capacity.

After analyzing the pallet movement transactions and usage of the onsite warehouses, the manufacturer found that there were a relatively high number of pallets moving back and forth between the onsite locations and offsite warehouse, and the onsite capacity was not fully utilized. Therefore, in order to improve the item accessibility and reduce the transportation cost, the manufacturer decided to bring in more fast moving pallets (i.e. high consumption) from the offsite storage to the onsite storage, and also decided to receive and store some specific products onsite.

The data provided includes pallet movement transactions and the current inventory level at each warehouse for one year. The inventory levels were then rolled back by the rollback algorithm presented in Chapter 3, in order to obtain the historical inventory levels for the models. The procurement schedule, production consumption schedule and production outcomes were extracted from the pallet movement transactions. For this experiment, 1,470 materials are included.

The owned warehouse capacities are summed to yield the onsite warehouse capacity. Two cost parameters, storage rental cost per pallet per time and transportation cost per pallet, are estimated through a material-flow analysis. The estimated storage rental is $0.2 per pallet per day. The estimated transportation cost is $4.9 for each pallet transferred between onsite locations and the offsite storage. These values are utilized in the experiments in the next subsection.

4.5.2 Experimentation Description

The experiment is carried in two steps. First, the material location policies are created. Second, the policies are employed and the total costs are calculated in order to observe the performance of these models with respect to current procurement and production plans.

4.5.2.1 Policy generation

The one-year worth of data, including procurement schedule, production schedule, inventory level, and inbound and outbound shipments, is split into four datasets according to the calendar quarters (i.e. 3 months each). Each set is used to create a material-location policy that is used for the next three months (i.e. next calendar quarter). For example, the January – March data is used to create material-location policies that will be used by the warehouse manager from April until June. Then, the April – June data is used to create material-location policies that will be used by the warehouse manager from July until September. Note: the item level and item shipment level models do not create a material location policy, because they are proposed for the situation in which the warehouse manager decides to handle items and item shipment according to their expertise and available information.

4.5.2.2 Model Evaluation

To evaluate the performance of each model, material flow decisions are fixed for every model. In essence, the material flow decisions are assumed to be carried out optimally with respect to material-location policies. However, in order to achieve that, the models have to be modified as follow.

1) For all five models, the initial inventory level of each warehouse (i.e. $t = 0$) is set to the ending level in the previous dataset as follow:

$$q_{it}^{on} = Q_{it}^{on} \quad \forall i \in I, t = 0$$

$$q_{it}^{off} = Q_{it}^{off} \quad \forall i \in I, t = 0$$

2) For the material shipment level model, material level model, and hybrid material level model, the decision variables x_i are set according to the policies generated by each model.

3) For the material level model, constraint (4.43) (i.e. $q_{it}^{off} \leq (1 - x_i)M$) is dropped, since the number of onsite items might be higher than the warehouse

capacity, due to supply deliveries and production. To handle this situation, the onsite materials are allowed to be stored offsite, but the offsite items are still maintained offsite with respect to constraint (4.42) in order to maintain their collectiveness. Also, since moving items offsite induces a transportation cost, only excess inventory is expected to be moved offsite.

4) For the hybrid material level model, l_i is assigned with the values obtained after generating the policy.

Since the values for both decision variable x_i and onsite capacity limit l_i are known, the evaluation models for both the material shipping level and material level are linear programming (LP) models which can be solved optimally. For the hybrid level model there remains one integer variables (r_{it}), but they are only used for the onsite materials. Thus, the number of integer variables reduces significantly and can be solved quickly.

After creating material-location policies from each dataset, the policies were tested against each other by applying them to the modified models and running the modified models with monthly data. For example, the material level evaluation model was run with the April data and the policy created from the first dataset (i.e. Jan – March data), and then was run again with the May data with the same policy. Lastly, it was run with the June data with the same policy before starting again with the July data, but with the policy created from the second dataset.

In addition to being evaluated with the policies changed every 3 months, in order to observe the effect of material re-allocation on the transportation cost, the models are tested again with a single policy created from the first dataset. It was run with 9 sets of data from April until December. The result shows how the transportation cost is impacted by dynamically updating the policies with respect to current operations (i.e. procurement and production plans). Moreover, the results yielded by the item level model serve as lower bounds for other models. The item level model is used to represent the cost saving opportunity if the materials or items are individually assigned to locations.

4.6 Results and Discussion

The models were coded in C++ with Qt library and solved by GUROBI 4.2 under Window 7 64-bit environment with Intel i7 CPU Q740 processor with 4 CPU cores and 8GB of RAM. The results and discussion are shown for each experimental step.

4.6.1 Policy Generation

Since the hybrid material level model contains a relatively large number of integer variables, solving it for material-location policies to optimality would require a relatively high computational time. Therefore, the program was set to terminate after the optimality gap went under 5% (i.e. 0.05 gap). For the material level and material shipment level models, the termination gaps were set at 0.0001% (i.e. 0.00001 gap).

In the policy generation step, the cost results obtained by solving each model for each dataset are presented in Table 4.1. Also, the associated runtimes for each run are recorded (seconds). As expected, the hybrid material level spent significantly more time than the other models. However, for the last two quarters, Gurobi solved the hybrid material level model at 0.00% gap. The item and item shipment level models provide the lowest cost among the five models, while material level gave the highest costs.

Table 4.1Policy Generation Results

	1st Quarter		2nd Quarter		3rd Quarter		4th Quarter	
	Cost	Time (x100)	Cost	Time (x100)	Cost	Time (x100)	Cost	Time (x100)
Item	178,844.20	0.40	185,181.00	0.31	215,612.24	0.51	187,721.80	0.54
Item Shipment	178,955.72	32.10	185,200.40	18.52	215,637.64	8.84	187,889.20	11.77
Material Shipment	181,817.28	40.77	185,947.80	127.53	216,832.00	12.01	188,587.32	13.02
Material	322,476.12	22.90	194,840.60	81.35	337,128.85	84.49	198,973.76	66.63
Hybrid Material	202,837.64	1,377.60	195,069.84	1,338.18	232,703.20	1,203.01	197,539.12	367.22

4.6.2 Policy Evaluation

For evaluation purposes, each model was solved at 0.01% optimality gap (i.e. 0.0001 gap). Each material-location policy is applied for 3 months. The results are shown in Table 4.2. In addition to the results yielded by the five models, the original costs are calculated from the same data. Next to each cost column, the lower bounds were calculated by solving the item level model with the same dataset. Then, the results yielded by applying the policy generated from the first quarter dataset are shown in Table 4.3.

Table 4.2 Results of Quarterly Policy Updating

Quarterly Reallocation										
Month	**Original**	**Item**	**Item Shipment**		**Material Ship.**		**Material**		**Hybrid Material**	
	Cost	Cost	Cost	LB	Cost	LB	Cost	LB	Cost	LB
4	118,861	79,905	79,908	0.005%	83,718	4.77%	108,301	35.54%	93,688	17.25%
5	121,250	65,772	64,114	0.000%	68,939	3.56%	98,189	23.16%	81,378	23.03%
6	121,128	69,944	69,978	0.007%	74,971	7.36%	100,375	26.56%	93,829	33.25%
7	132,471	78,221	77,956	0.000%	81,253	4.36%	116,294	34.60%	116,526	48.57%
8	142,716	80,043	80,361	0.023%	87,722	8.91%	84,425	6.75%	98,716	21.17%
9	120,631	69,627	70,421	0.079%	76,620	8.41%	78,706	11.88%	85,310	18.52%
10	117,015	68,913	68,958	0.009%	71,655	2.67%	134,381	90.80%	96,189	36.14%
11	113,340	63,627	63,079	0.013%	69,166	8.13%	100,479	26.57%	78,891	23.78%
12	114,163	66,711	66,770	0.000%	71,520	6.77%	104,243	31.73%	84,189	25.10%
Total	1,101,574	642,763	641,546	-	685,563	-	925,394	-	828,716	-

Table 4.3 Result of Onetime Policy Updating

One Time Reallocation										
Month	**Original**	**Item**	**Item Shipment**		**Material Ship.**		**Material**		**Hybrid Material**	
	Cost	Cost	Cost	LB	Cost	LB	Cost	LB	Cost	LB
4	118,861	79,905	79,908	0.005%	83,718	4.77%	108,301	35.54%	93,688	17.25%
5	121,250	65,772	64,114	0.000%	68,939	3.56%	98,189	23.16%	81,378	23.03%
6	121,128	69,944	69,978	0.007%	74,971	7.36%	100,375	26.56%	93,829	33.25%
7	132,471	78,222	77,956	0.000%	82,752	6.29%	108,169	25.20%	95,014	21.14%
8	142,716	80,043	80,361	0.023%	85,961	6.70%	111,307	25.26%	102,605	26.12%
9	120,631	69,628	70,421	0.079%	72,336	3.72%	97,581	20.33%	89,381	21.46%
10	117,015	68,913	68,958	0.009%	70,115	2.67%	96,556	20.17%	82,858	17.68%
11	113,340	63,627	63,079	0.013%	66,172	4.30%	95,870	28.41%	77,833	20.51%
12	114,163	66,711	66,770	0.000%	72,949	9.85%	99,140	28.56%	84,838	26.39%
Total	1,101,574	642,763	641,546	-	677,913	-	915,488	-	801,423	-

According to the results, for both reallocation schemes, the material level policy yielded the highest total cost, followed by the hybrid material level policy, and then the material shipment level policy. For the item level policy and item shipment level policy, their costs are roughly the same. However, the total cost yielded by the item shipment policy is slightly lower. The cause behind this lower cost is the differences in the monthly starting inventories in each warehouse (i.e. having some months that the item level policy performs better and other months that the item shipment performs better). In addition, compared to the lower bounds, the results yielded by the item shipment level policy are relatively similar to the results of the item level policy. This may imply that if the procurement and production schedules (i.e. in this case they are monthly schedules) are available to the warehouse manager, periodically deciding where to receive each shipment could result in relatively low transportation cost and space rental cost, compared to the case in which each item is assigned to a location individually – item level policy. However, such a situation is not always possible and also requires the warehouse manager to repeatedly make decisions. In this case, the manager may adopt a material-location policy that specifically identifies a delivery location for each material, instead of deciding for each shipment. Because of this, three more policies are examined: material shipment level policy, material level policy, and hybrid material level policy.

The material shipment level policy, consolidating all shipments of the same material at one location, yielded the lowest cost among the three policies. In addition, the material shipment level policy results in cost around 6% different to the item shipment level policy, comparing to approximated 40% and 25% from the material level policy and the hybrid material level policy, respectively. This implies that as the storage locations of the materials are not fixed, the warehouse manager can achieve relatively low transportation cost and storage rental cost that are similar to the item shipment level policy, which periodically decides where to receive each shipment individually. Of course, this result is made after assuming that the warehouse manager carries out the material flow operations according to the optimal plan suggested by the models, but it also denotes the best possible outcome that could be achieved if the policy is employed.

In the case that the storage locations of materials are considered, the material location policy, defining both delivery and storage locations for each material, yielded the highest cost among the five policies, which is around 45% higher than both item shipment and item level policies. Meanwhile, the hybrid material level policy defines an onsite storage limit for each material and tries to maintain the onsite material collectiveness by replenishing the onsite material inventories from the offsite storage. The hybrid policy yielded costs around 10% lower than the material level policy and around 29% higher than both item shipment and item level policies. These higher costs are suspected to stem from the transshipments that replenished the onsite inventories from the offsite storage. Compared with the original costs, all five models yielded lower costs, but the differences decrease as more restrictions were introduced. The total cost differences range from $170,000 to $460,000 among five different models during April to December.

Comparing the costs between the two re-allocation schemes (i.e. re-allocating materials every 3 months and once a year), the results show that the quarterly re-allocation yielded around 1-3% higher cost than the one time reallocation. The reason behind it seems to come from the seasonality effect of the product demand, since using a quarterly dataset may not represent the future demand. Figure 4.3 shows the demands of four items selected from 20 most requested ones. As the demand for each product fluctuates, the material-location plan may change from quarter to quarter. For example, as material D had not been requested until April, this material might not be selected by the model until the policy was recreated at the end of June. So, its items would be received offsite until then. Similarly, the demand for material A was at bottom of the chart during April until June, but its demand was relatively high during the first three months. As such, the material A might be selected to be received onsite by the model that generates the policies with the first quarter dataset. However, the material A would not be used until October. In this case, the future transportation and storage cost savings might not be high enough to compensate the reallocation costs. In order to observe this effect, the costs yielded by the models are broken down, and shown in Tables 4.4 and 4.5.

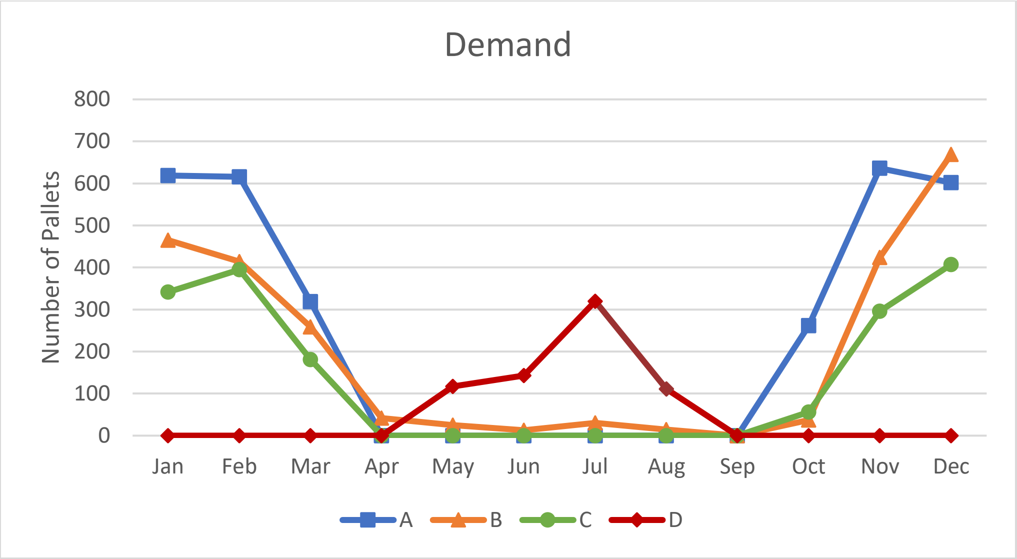

Figure 4.7 Demand Fluctuation for Material A, B, C and D

According to the results, after the material-location plan was created from the second quarter dataset (i.e. April – June) and applied during July until September, costs to re-allocate the items are reflected in the July transportation costs. As opposed to the July transportation costs in the onetime policy updating scheme (i.e. $14,347 for the material level policy and $19,513 for the hybrid material level policy), the July transportation costs are more than double for material level policy, $40,191, and hybrid material level policy, $42,430. However, the transportation cost savings that come after the reallocation (i.e. $16,000 and $6,100 for material level policy, and hybrid material level policy, respectively) are not large enough to cover these increases. For the material shipment level policy, the total costs of both transportation and space rent are approximately the same between both reallocation schemes. However, the onetime reallocation scheme provides around 0.5-3% lower costs for both storage rent and transportation.

In term of the storage rental cost, the material level policy yielded the highest total cost, approximately $770,000. As explained in section 4.3, the drawback of the material level policy is relatively lower space utilization than the other methods, since the purpose of this method is to provide ease of implementation by specifically defining a location for each material and maintaining each material in one location. In contrast, the material shipment level policy yielded the lowest total storage cost, approximately $590,000, because the storage location of each item can be decided freely, compared to the material level policy. The hybrid material level policy, which tries to utilize the onsite floor space by continuously replenishing the onsite material inventories, but still allows the non-onsite materials to move between the warehouses, yielded a storage cost of around $607,000. Compared with the storage costs between the two policy-updating schemes, the total storage costs of the same policy are relatively similar. Except for the hybrid material level policy, whose storage cost for one-time reallocation scheme is around 0.6% higher, the other material-related policies with one-time reallocation have the total storage costs around 0.7-4% lower.

Table 4.4 Solution Cost Breakdown for Quarterly Policy Updating

Quarterly Reallocation						
Month	**Material Ship.**		**Material**		**Hybrid Material**	
	Trans.	Rent	Trans.	Rent	Trans.	Rent
4	24,049	59,669	24,403	83,898	33,589	60,099
5	7,434	61,505	11,139	87,050	17,368	64,011
6	9,132	65,840	12,935	87,440	25,722	68,107
7	7,877	73,376	40,191	76,103	42,430	74,096
8	11,862	75,860	6,686	77,739	21,860	76,857
9	9,451	67,168	6,066	72,640	16,202	69,109
10	5,830	66,521	41,800	92,581	30,976	65,213
11	6,691	60,292	13,756	86,723	17,190	61,700
12	8,251	63,269	14,111	90,132	18,588	65,601
Total	90,577	593,500	171,088	754,306	223,924	604,792

Table 4.5 Solution Cost Breakdown for Onetime Policy Updating

	One Time Reallocation					
Month	**Material Ship.**		**Material**		**Hybrid Material**	
	Trans.	Rent	Trans.	Rent	Trans.	Rent
4	24,049	59,669	24,403	83,898	33,589	60,099
5	7,434	61,505	11,139	87,050	17,368	64,011
6	9,132	65,840	12,935	87,440	25,722	68,107
7	9,481	73,272	14,347	93,822	19,513	75,501
8	10,362	75,599	16,093	95,214	23,960	78,645
9	6,214	66,122	12,738	84,843	20,192	69,189
10	5,117	64,998	11,341	85,215	15,493	67,364
11	6,691	59,480	14,824	81,046	16,516	61,317
12	9,825	63,124	11,985	87,155	20,448	64,390
Total	88,304	589,609	129,804	785,683	192,800	608,623

In addition to the cost breakdown of the material shipment level policy, material level policy and hybrid level material level policy, the cost breakdown of the item level policy, item shipment level policy and actual operations (original) are given in Table 4.6. Both item level and item shipment level policies resulted in approximately the same costs. That is because both methods do not restrict the location of items while the item shipment level policy only determines a receiving location for each shipment, not for each material. Compared to the actual operations, all five policies yielded lower total transportation costs (i.e. range from 28% lower to 400% lower) and storage costs (i.e. ranged from 8 to 39% lower). As the material level policy sacrifices space utilization for ease of implementation and maintenance, it yielded only 8% lower total storage cost, but 67% lower total transportation cost than the original operations.

Nevertheless, the material shipment level policy is still be able to maintain relatively close transportation cost to the item level and item shipment level policies. This is because once items are received at one location, they are rarely moved to another location until they are called by production or outside demands. Since the model's objective is to minimize the overall cost, which is the summation of rent and transportation costs, and depending on the time duration in which an item is stored offsite, moving the item to the onsite storage location would require transportation cost.

Table 4.6 Solution Cost Breakdown for Actual Operation, Item Level Policy, and Item Shipment Level Policy

Month	**Original**		**Item**		**Item Shipment**	
	Trans.	Rent	Trans.	Rent	Trans.	Rent
4	30,824	88,037	19,714	60,190	19,714	60,194
5	30,794	90,456	4,458	61,315	2,799	61,315
6	30,258	90,870	4,187	65,757	4,216	65,762
7	36,418	96,054	5,013	73,208	4,748	73,209
8	43,827	98,889	4,763	75,281	5,077	75,284
9	29,751	90,879	3,685	65,942	4,472	65,949
10	27,468	89,546	4,423	64,490	4,467	64,491
11	29,244	84,095	4,212	59,415	3,656	59,423
12	27,468	86,694	3,587	63,124	3,646	63,124
Total	286,054	815,521	54,041	588,722	52,797	588,749

The above experiments applying five material location policies to the actual operations of a real manufacturer showed that there is a cost saving potential that can be gained from solving the material location problem. The potential cost savings that the policies could provide range from 15% to 40% over the actual operations. In this study case, the warehouse manager determines where items will be stored, which is similar to the item level or item shipment level policies (i.e. except that these two use optimization models to determine the locations). However, as mentioned in Section 4.2, these two policies require the warehouse manager to have relatively accurate information on the timing of material procurement and production, so they are relatively harder to handle properly compared to the material shipment level, which provides a comparable cost saving with a relatively solid rule for managing the material locations.

4.7 Summary and Conclusions

In this chapter, the material location selection problem is introduced to allocate materials to two warehouses. One is owned by the manufacturer and the other is rented for storing inventory excess. To solve the problem, five models with different selection criteria are proposed as decision support tools for a warehouse manager to determine item receiving locations and item storage. The models try to balance the use of 3PL warehouses by effectively utilizing the owned storage, and also aim at minimizing the space rental and transportation costs that may be incurred by storing fast moving items offsite, causing a firm to repetitively transship items to the onsite production plant.

The proposed models were tested with real industrial data and two policy updating schemes. The results showed that the cost saving on transportation and storage decreases as the level of item selection restrictions increases. In addition, as the demand changes seasonally, repeatedly updating the policies could become an expensive operation, because the set of items at each warehouse may change from one period to another, leading to the expensive item reallocation cost that incurs by moving items between the warehouses.

In case that the demand consists of both regular and seasonal demands, to handle the changes in the demand, the data that is used to create a material location policy has to be large enough to cover the demand cycle. For example, the demand for agricultural products may change throughout a year, due to agricultural seasons. In this case, one year’s worth of data may be used to create the policy. In other cases, the warehouse manager may reserve an area for seasonal products, so a material location policy can be created separately for year-round products. Also, further analysis is needed that looks into the seasonality of demand and policy re-evaluation by expertise (i.e. warehouse manager).

In conclusion, the 15% to 40% cost saving potential that these five material location policies could provide over the actual operations establish an incentive to have a solid material location rule for managing the storage of rented and owned warehouses. In the next chapter, a two-warehouse material location selection model that utilizes historical space usage of the warehouses for creating a material-location plan is developed. In addition, the use of two warehouses is integrated into production planning in order to study the cost effect of using them. As a side application of these models, in Chapter 6 the models are used to determine the additional storage space that could be installed into the owned warehouse in order to balance the use of both warehouses.

CHAPTER 5

INTEGRATED TWO WAREHOUSE PRODUCTION PLANNING

5.1 Introduction

The decisions made by the material location selection models presented in Chapter 4 are driven by the differences in the inventory holding costs between onsite and offsite warehouses, and by the transportation cost resulting from moving items between locations. In this chapter, the two warehouses are integrated with production planning in order to observe a potential cost saving. To achieve this, the network flow model presented in Chapter 4 for material-location selecting is extended to include production planning. The impact of incorporating two warehouses that have different material holding cost rates and transportation cost is analyzed.

In the literature reviewed in Chapter 2, a single warehouse is commonly used with the inventory holding cost charged for each unit of a material stored in the warehouse. The transportation cost for transporting items between locations is rarely mentioned. However, in the situation where a company decides to rent a warehouse for additional storage space, materials have to be transported from the rented warehouse to the production site. There is an incentive to allocate frequently used materials close to the production plant for quick accesses and in order to avoid transportation cost (Wutthisirisart et al., 2012). In addition, each warehouse may have different storage capabilities and characteristics (e.g. humidity control, item tracking, insurance, etc.), which can result in different deterioration rates and holding costs. Therefore, not considering transportation cost and different holding cost rates may limit the opportunity to minimize the overall cost.

The literature that is most closely related to the production planning problem and accounts for location-dependent holding cost rates is found in the supply chain network problem in which items are distributed from the production plant to multiple storage locations known as distribution centers. It is also similar to the inventory control problem in which a warehouse is rented for excess inventory that resulted from high volume purchases. However, both problems specialize in different areas of business operations and management. The former problem focuses on distributing items from production downstream through the supply chain network until reaching customers. Although it considers transportation cost and location dependent holding cost, items are moved in a single direction; by starting from suppliers, then to production, and finally to customers.

The two-warehouse inventory control problem focuses on creating an order policy. It allows additional storage space to be rented for high-volume purchases that can lower per-item purchase cost (i.e. economies of scale where a material is sold or purchased with a lower unit price in exchange for a higher volume purchase). Even though the inventory control problem is a well-studied problem, the literature reviewed in Chapter 2 showed that the models with two warehouses perform at the aggregate production planning level, which considers a single material or materials as a group. In addition, they do not differentiate material types (i.e. raw materials, semi-finished goods or work-in-process, and finished goods), which will later be shown to have different flow directions. In particular, the goal of the inventory control problem focuses on setting up an ordering policy to assist warehouse managers in determining when to order/produce and how much to order/produce a commodity.

A production system consists of multiple types of materials (i.e. raw material, semi-finished goods, and finished goods). Each of these materials has different flow direction, either into or out from the same facility. For example, raw materials ideally move from the warehouse to the production plant, which is a point of consumption; finished goods move from production to a warehouse or directly to a distribution center; semi-finished goods move from a production plant to a warehouse and back to the production plant for additional processes. With a single warehouse, transportation cost is typically not included in production planning, but with two warehouses, especially when the rented warehouse is located offsite and further away from the production plant, the transportation cost can affect the overall cost when items are repeatedly moved back-and-forth between the onsite locations and offsite storage.

In addition to proposing an integrated production planning model with two warehouses and material flows, a material location selection model will be developed in this chapter to create a material location plan that can guide material storage operations. Without a material location plan, the decision on where materials will be stored and which warehouse will supply materials to production relies on the expertise of the warehouse management team. However, with actual material movement data, Chapter 4 showed that doing so may mislead the team about its actual warehouse usage level, and may, for this particular case study, result in 16% to 40% higher material transportation and inventory holding costs than when material location plans are developed.

In this chapter, the material location selection models presented in Chapter 4 are used as the base-model to develop the production planning model with two warehouses and material flows and material location selection. The production model is formulated as a material requirement planning model (MRP) integrated with two warehouses and material flow constraints as presented in Chapter 4. In addition, the material location selection model is formulated based on the ideal flows of each material type and using historical or estimated future material movement activities to allocate materials to warehouses.

This chapter is organized as follows. Section 5.2 describes the production planning problem considered in this study. Then, an integrated two-warehouse production planning model is proposed in section 5.3. Next, the material location selection model is given in section 5.4. Section 5.5 describes the data that is used by the models. The results are reported in section 5.6 with comparison between the plans generated with knowledge of two warehouses, and the plans that are created without considering them. In addition, a comparison is provided between the cases when the material-location layout is applied in the planning process, and when the materials are allowed to be stored in any warehouse. Section 5.7 provides a discussion related to the applicability of the model and summarizes the findings of the chapter.

5.2 Problem Characteristics

The production system considered in this study consists of two warehouses. One of them is owned by the company, and the other is rented through a third-party logistics provider (3PL). Three kinds of materials are assumed:

- Raw materials are bought directly from suppliers and are not considered to be salable products.
- Semi-finished goods materials are parts or work-in-process materials produced from multiple raw materials or semi-finished goods materials. Some of them can be sold as parts or supplies for other businesses' production.
- Finished goods are final products that are not part of any other product production.

Material items are stored in one of the two production warehouses. One of them is owned by the company. The other one is rented through a third-party logistics provider (3PL) who is responsible for handling and transferring the items. The rented warehouse is located off the production site and also referred to as an offsite warehouse. It is assumed that the 3PL charges the company for each item stored in the rented warehouse and for each item transported between the warehouse and the production site. In addition, the inventory holding cost of each material is assumed to be different for each warehouse, since the warehouses are not only different in term of ownership, but also their storage environment. For example, one warehouse may be equipped with specialized equipment such as humidity control, which provides a better environment for perishable items than warehouse without humidity control.

To produce one unit of a material (i.e. both semi-finished and finished goods, but not raw material), the material's production follows a sequence of processes. Each process requires multiple materials and resources (i.e. equipment and machine) and cannot start without acquiring them. Once the resources are available, they are seized for a defined amount of time before being released back for other production to use. If some of the resources are used by other production processes, then the production that requested these resources must wait in queue until they are released.

Figure 5-1 illustrates a sequence for processes of material M1's production. Process 2, for example, consumes two units of material M2 and three units of material M3 in order to produce one unit of M1. Also, it will seize 1.25 units of resource R1 and 0.25 units of R2. Figure 5-2 shows material dependencies, which can be found in a Bill of Material (BOM). An item of a material is composed of multiple items of other materials. Also, a material can be part (or a production ingredient) of multiple other items. For example, M5 is an ingredient for producing M3 and M4.

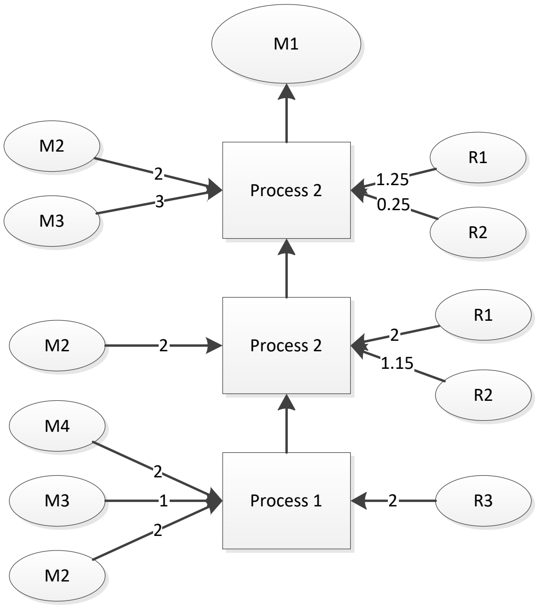

Figure 5.1 Production of material M1 is a sequence of processes in which each of them requires a certain number of different material items and processing time on different resources.

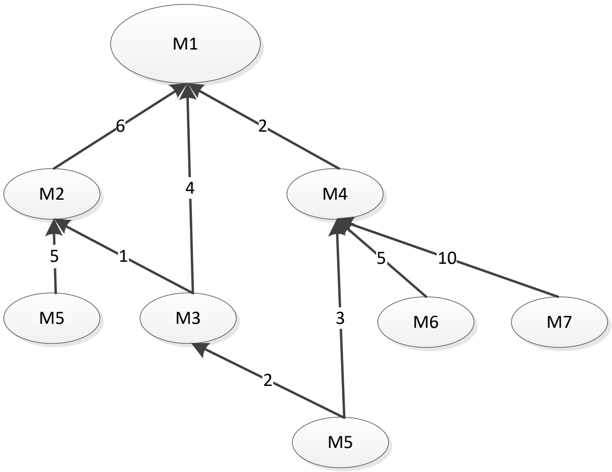

Figure 5.2 Illustration depicting the material dependencies of each material's production.

Since a material’s production shares multiple resources with other production processes, it must wait until those resources, as well as the required materials become available. Therefore, its’ production lead time depends on the workload of other material production. This kind of lead time is also known as workload-dependent lead time in which it increases nonlinearly before the resource utilization reaches the maximum level (Pahl et al., 2007).

In a production system with two warehouses, each process’s lead time determines when items are transported and consumed. To estimate the transportation cost and inventory holding cost while capturing the material requirement dependencies (Figure 5.2), the concept of material resource planning (MRP) is integrated with two warehouses and material flow related constraints in the material-location selection model presented in Chapter 4.

5.3 Two-warehouse Material Resource Planning Model

In this section, the classic material resource planning model is modified to include two warehouses and material flows in order to capture the warehouse-dependent inventory holding cost and material transportation cost. The solution method applies the concept of an effective loading ratio proposed by Kim and Kim (2001) to account for the workload dependent lead time. The ratios cause the quantities scheduled for production to be spread across subsequent periods, and only a partial amount of each resource's capacity can be utilized in each period due to material queuing. The production planning approach that considers two warehouses is discussed in section 5.3.1. Then, its' formulation is given in section 5.3.2.

5.3.1 Two-warehouse Material Resource Planning Model

In the case where each material does not have a dedicate production line with all necessary resources dedicated to it, the order released to the production system needs to wait in queues for resources and required materials to become available, leading to delays in completing the order. The result is that, an order released in one period may become effective in other periods. In addition to delaying the production output, the queueing also delays the use of resources that have already been seized by a production plan, since production cannot start until all necessary resources are acquired. Consequently, the resource capacity that is typically expressed as a constant term in the classic MRP model cannot be fully utilized.

Queueing for resources and other materials prolongs the lead time of material production in addition to its' processing time, in this study, the proposed solution method applies a hybrid simulation-optimization approach similar to that of Huang and Leachman (1996), Byrne and Bakir (1999), and Kim and Kim (2001), in order to estimate the quantities of materials that can be produced in each subsequent period after orders have been released to the production system. The estimated quantities of a material produced in each period is calculated through a simulation model as a ratio between the quantity released in a period and the quantities that can be produced in each subsequent period. The ratio is termed the “effective loading ratio”. Figure 5.4 illustrates the concept of the simulation-optimization approach used in this study.

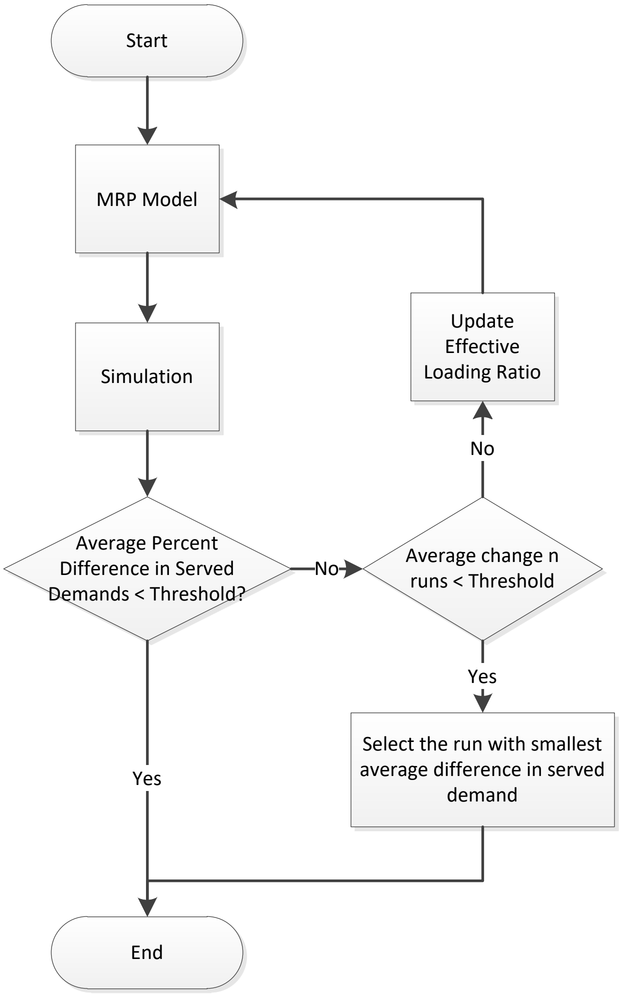

Figure 5.3 Integrated two-warehouse production planning algorithm flow-chart; creating a production plan by optimizing the cost through an optimization model and then executing the plan in simulation to analyze feasibility.

The algorithm starts by optimizing the modified MRP given in the next section. The production plan generated by the modified MRP is then executed by the simulation model that simulates operations of the production system. While the simulation executes the production plan, it collects information about released and produced quantities of each material, which are later used to calculate effective loading ratios. The ratios are then incorporated back into the MRP model. The algorithm runs until a defined stopping criteria is met.

The MRP model in Figure 5.4 is developed by extending the material location selection model presented in Chapter 4. This enables the model to consider transportation cost, which is a result of transporting items between onsite and offsite storage locations, and also consider the differences in holding cost rates between the two warehouses. The following aspects of the two-warehouse production planning problem are incorporated into the model.

- The model includes two warehouses.
- Material flow activities are represented as network flows between locations.
- The transportation cost rate is assumed to be dependent on materials, since materials may have different size and weight.
- The inventory holding cost rate of a material is assumed to be material-location dependent, since one warehouse may specialize in certain kinds of activities that provide a better storage environment than the other (such as shared freezer, humidity control, and insurance for high cost items).
- Each period is split into multiple sub-periods. Figure 5.4 illustrates the two different time scales in which the upper part represents 3 time periods (i.e. $p \in$

$\{1,2,3\}$), and the lower part represents 15 sub-periods (i.e. $t \in \{1,2,3, \dots 15\}$). Note the zero period and zero sub-period represent the beginning of the planning horizon.

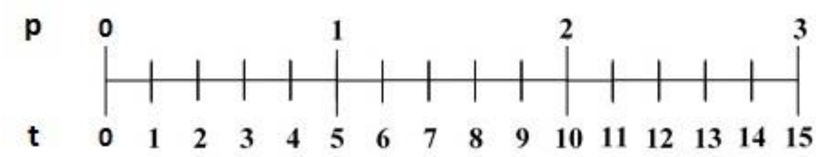

Figure 5.4 Time scale considered in this study consists of multiple sub-periods which are grouped into multiple time periods.

The sub-period scale is used to estimate the material flow/movement activities, which are short term planning and scheduling decisions, such as which storage locations shall supply materials to production or which storage locations will accommodate the materials recently produced from the production plant. On the other hand, the period time scale determines production planning decisions, which specify how much to produce and how much to purchase. The production planning decisions may affect operations, both production and material movements in subsequent periods and sub-periods from when the production decisions have made, due to the workload dependent lead-time.

By separating the planning timeline into two time scales, the planning decisions and modelling parameters are also separated into two kinds based on the time scale in which they operate. Planning decisions refer to the variables of interest in which their values need to be determined, such as material quantities to be produced, stored and transported. Modelling parameters refer to the constant values that limit the production behavior, such as resource capacity, warehouse capacity, holding cost rate and transportation cost rate. The first kind of planning decisions and parameters operating on the period time scale includes:

- Material procurement decision; deciding the quantities of raw materials delivered in each period
- Backlog penalty; expressed in form of a monetary value charged for each unit of demand that cannot be produced by the end of each period
- Resource capacity; defined as the operational hours that are available to a resource within a period.

The second kind of planning decisions and parameters operating on the sub-period time scale includes:

- Material flows; balancing the warehouse inventories accordingly to operations in the production system, such as demand serving, material supplying, product storing etc.
- Backlog flows; refers to the amount of demand that cannot be satisfied in a sub-period and will possibly be produced in future sub-periods.
- Production activities; includes production demand for materials and storage demand for produced items.

At the end of each simulation run, the algorithm calculates across previous iterations the total number of items processed in each sub-period by each machine in each production process. To calculated the effective loading ratios, the following sets are declared:

- A is a set of iterations that have been run, including the current iteration.
- P is a set of periods.
- T_p is a set of sub-periods in period p.

The following terms represent the information collected from the simulation:

- α_{arp} is a fraction of the resource r's capacity that was used in period p of iteration a.
- $\beta_{aij(s,p)}$ is the number of items in material i order of iteration a that are released in period s, and processed by process j in period p.
- $\gamma_{aijr(s,p)}$ is the number of items in material i order of iteration a that are released in period s and processed by process j with resource r in period p.
- g_{aip} is the number of items in material i order released in period p of iteration a.

Then, the effective loading ratios in this study are defined as follows:

- $\bar{u}_{rp}$ is the weighted average fraction of resource r's capacity that can be used in period p (Equation 5.1).
- $\bar{e}_{ij(s,p)}$ is the weighted average proportion between the total number of items in material i orders that are released in period s, but processed by production process j in period p, and the total number of items in material i orders that are released in period s (Equation 5.2).
- $\bar{e}_{ijr(s,p)}$ is the weighted average proportion between the total number of items in material i orders that are released in period s, but processed by production process j in period p with use of resource r, and the total number of items in material i orders that are released in period s (Equation 5.3).
- $\bar{\lambda}_{ijpt}$ is the weighted average proportion between the total number of material i processed by production process j in sub-period t during period p, and the

total number of material i processed by production process j in period p (Equation 5.4).

$$\bar{u}_{rp} = \frac{\sum_{a \in A} \alpha_{arp}}{|A| \cdot K_{rp}} \qquad (5.1)$$

$$\bar{e}_{ij(s,p)} = \frac{\sum_{a \in A} \sum_{t \in T_p} \beta_{aij(s,p)t}}{\sum_{a \in A} g_{ais}} \qquad (5.2)$$

$$\bar{e}_{ijr(s,p)} = \frac{\sum_{a \in A} \gamma_{aijr(s,p)}}{\sum_{a \in A} g_{ais}} \qquad (5.3)$$

$$\bar{\lambda}_{ijpt} = \frac{\sum_{a \in A} \sum_{s \leq p} \beta_{aij(s,p)t}}{\sum_{a \in A} \sum_{s \leq p} \sum_{t \in T_p} \beta_{aij(s,p)t}} \qquad (5.4)$$

The loop in Figure 5.3 repeats until the weighted average of relative differences (or percentage difference) in the accumulated amounts of demand served by the MRP model and the simulation is less than or equal to a defined threshold. An accumulated amount of the material's demand served is the total amount of such material that has been used to satisfy its demand up to the end of a defined time period. The relative difference of accumulated amounts served by the MRP and the simulation until a given time period is the difference between the total demands served by the MRP and the simulation, divided by the maximum amount between them. Their average value is defined in the formulation as follows:

- P is a set of time periods.
- T_p is a set of sub-periods in period p

- d_{it}^{MRP}, d_{it}^{Sim} are the amounts of material i demand served in sub-period t by the MRP model and the simulation model, respectively.
- $\bar{d}_i$ is the average of relative differences in the accumulated amounts of material i demand served by the MRP and the simulation.

$$\bar{d}_i = \frac{\sum_{p \in P} \frac{\left|\sum_{s \leq p} \sum_{t \in T_s} d_{it}^{MRP} - \sum_{s \leq p} \sum_{t \in T_s} d_{it}^{Sim}\right|}{\max(\sum_{s \leq p} \sum_{t \in T_s} d_{it}^{MRP}, \sum_{s \leq p} \sum_{t \in T_s} d_{it}^{Sim})}}{\text{Number of Periods}} \qquad (5.5)$$

The loop in Figure 5.3 continues until the average value of $\bar{d}_i$ (i.e. weighted average value of relative differences) across different materials is less than or equal to a defined threshold. Note the relative difference can assume different denominators instead of the maximum term in Equation 5.5; for example, the minimum value between its subtraction terms, or an average value between its subtraction terms. In addition to using the accumulated demands served in Equation 5.5 as a stopping criteria, different criteria can be used such as the feasibility of resource capacities as described the work of Kim and Kim (2001). The served amount of demand is used in this study in order to obtain the plan that potentially has a low level of discrepancy between the demands served in the execution phrase and the demands served in the production plan. In other words, the algorithm iterates until the production plan generated by solving the optimization model yields a relatively close amount of served demands to the amount estimated by the simulation model, which simulates real production operations. This estimation of served demands approximated by the algorithm can benefit the marketing and sale departments when they try to negotiate a sale contract with customers.

5.3.2 Notation and Formulation

With the integration of material transportation and two warehouses, the two-warehouse material production resource planning model can be formulated with the following notation:

Sets:

P : set of time periods (i.e. $P = \{1,2,3,\dots,m\}$);

T : set of sub-periods (i.e. $T = \{1,2,3,\dots,n\}$);

T_p : set of sub-periods in period p;

M : set of materials;

B_i : set of processes in material i production

R : set of resources;

R_{ij} : set of resources used by process j of material i production;

RW : set of raw materials;

FG : set of finished goods materials;

SG : Set of semi-finished goods materials;

Parameters:

C_i^{HF} : offsite inventory holding cost rate of material i;

C_i^{HO} : onsite inventory holding cost rate of material i;

C_i^B : backlog cost rate charged for each unit of material i demand that is satisfied in each period;

C_i^T : transportation cost rate of material i;

K_{rp}^R : total capacity of resource r available in period p;

K^O : onsite warehouse storage capacity;

U_{ijr}^R : resource r usage rate for producing one item of material i in process j;

U_{il}^M : number of material i items for producing one item of material l;

D_{ip} : demand for material i in period p;

F_{ipt} : fraction of material i demand in period p expected to be delivered in sub-period t;

I_i^{on} : initial inventory of material i stored onsite;

I_i^{off} : initial inventory of material i stored offsite;

Simulation Captured Parameters:

$\bar{e}_{ij(s,p)}$: weighted average proportion between the number of material i orders released in period s and processed by process j in period p;

$\bar{e}_{ijr(s,p)}$: weighted average fraction of material i orders released in period s and processed by process j with resource r in period p;

$\bar{\lambda}_{ijpt}$: weighted average fraction of material i orders in which process j is done in sub-period t during period p;

$\bar{u}_{rp}$: weighted average fraction of the resource r's capacity that can be used in period p

Variables:

g_{ip} : the number of material i items released as a production order in period p;

τ_{it}^{on}: the number of material i items moved from onsite storage to offsite storage in sub-period *t*;

τ_{it}^{off}: the number of material i items moved from onsite storage to offsite storage in sub-period *t*;

ρ_{it}^{on}: the number of material i items moved from onsite storage to production plant in sub-period *t*;

ρ_{it}^{off}: the number of material i items moved from offsite storage to production plant in sub-period *t*;

q_{it}^{on}: the number of material i items stored onsite at the end of sub-period *t*;

q_{it}^{off}: the number of material i items stored offsite at the end of sub-period *t*;

g_{it}^{on}: the number of material i items moved from production plant to onsite storage in sub-period *t*.

g_{it}^{off}: the number of material i items moved from production plant to offsite storage in sub-period *t*.

v_{it}^{on} : the number of material i items received at the onsite storage in period p

v_{it}^{off} : the number of material i items received at the offsite storage in period p

d_{it}^{on}: the number of material i items serving customer demands from onsite storage in sub-period *t*;

d_{it}^{on}: the number of material i items serving customer demands from offsite storage in sub-period *t*;

d_{it}^{B} : the backlog quantity of material i at the end of sub-period t

The network model for selecting material locations presented in Chapter 4 is integrated with production decisions in the following. Note $|set|$ refers to the cardinality of a set, and also refers to the last element within the set that contains a sequence of numbers starting from one; for example, a set of processes contains 1, 2 and 3 (i.e. {1,2,3}) to represent process 1, 2 and 3 of a material's production.

The objective function (5.6) focuses on minimizing the total cost that is a combination of transportation cost, inventory holding cost and backlog penalty cost while subject to constraints 5.7 – 5.18. Constraint 5.7 limits the use of resource r within its capacity adjusted by the fraction term $\bar{u}_{rp}$. The total amount of resource r's capacity used in period p is calculated as the total number of items whose orders were released into the production system prior to period p and are being processed in period p, times the resource usage rate U_{ijr}^{R}. Constraint 5.8 distributes the items produced in each sub-period to onsite and offsite warehouses. The quantities produced in period p are the total number of items that have their last production process $|B_i|$ finished in period p. These quantities are then distributed proportionally to different sub-periods of period p with respect to the proportions $\bar{\lambda}_{ijpt}$.

$$\min \sum_{i\in M}\sum_{p\in P}\sum_{t\in T_p}\left(q_{it}^{off}C_i^{HF}+q_{it}^{on}C_i^{HO}\right)+\sum_{i\in M}\sum_{p\in P}\sum_{t\in T_p}\left(\tau_{it}^{on}+\tau_{it}^{off}+g_{it}^{off}\right)C_i^{T}+\sum_{i\in M}\sum_{p\in P}d_{i\,max(T_p)}^{B}C_i^{B} \qquad (5.6)$$

Subject to:

$$\sum_{i\in M-RW}\sum_{j\in B_i}\sum_{s=1}^{p} g_{is}\bar{e}_{ijr(s,p)}U_{ijr}^{R}\le \bar{u}_{rp}K_{rp} \qquad \forall r\in R, p\in P \qquad (5.7)$$

$$g_{it}^{on}+g_{it}^{off}=\sum_{s=1}^{p} g_{is}\bar{e}_{i|B_i|(s,p)}\bar{\lambda}_{ijpt} \qquad \forall i\in\{M-RW\}, p\in P, t\in T_p \qquad (5.8)$$

$$\rho_{it}^{on}+\rho_{it}^{off}=\sum_{l\in\{M-RW\}}\sum_{j\in B_l}\sum_{s=1}^{p} g_{ls}\bar{e}_{lj(s,p)}\bar{\lambda}_{ljpt}U_{li}^{M} \qquad \forall i\in\{M-FG\}, p\in P, t\in T_p \qquad (5.9)$$

$$F_{ipt}D_{ip}+d_{i(t-1)}^{B}-d_{it}^{B}=d_{it}^{on}+d_{it}^{off} \qquad \forall i\in\{M-RW\}, p\in P, t\in T_p \qquad (5.10)$$

$$q_{it}^{on}=q_{i(t-1)}^{on}-\tau_{it}^{on}+\tau_{it}^{off}+g_{it}^{on}-\rho_{it}^{on}-d_{it}^{on}+v_{it}^{on} \qquad \forall i\in M, t\in T \qquad (5.11)$$

$$q_{it}^{off}=q_{i(t-1)}^{off}+\tau_{it}^{on}-\tau_{it}^{off}+g_{it}^{off}-\rho_{it}^{off}-d_{it}^{off}+v_{it}^{off} \qquad \forall i\in M, t\in T \qquad (5.12)$$

$$0\le v_{it}^{on}, v_{it}^{off} \qquad \forall i\in RW, p\in P, t=\min\left(T_p\right) \qquad (5.13)$$

$$0\ge v_{it}^{on}, v_{it}^{off} \qquad \forall i\in RW, p\in P, t\ne \min(\mathrm{T_p}) \qquad (5.14)$$

$$0\ge v_{it}^{on}, v_{it}^{off} \qquad \forall i\in M-RW, p\in P, t=\mathrm{T_p} \qquad (5.15)$$

$$q_{it}^{on}=I_i^{on} \qquad t=0 \qquad (5.16)$$

$$q_{it}^{off}=I_i^{off} \qquad t=0 \qquad (5.17)$$

$$x_{it}^{on}, x_{it}^{off}, g_{it}^{on}, g_{it}^{off}, g_{ip}, \rho_{it}^{on}, \rho_{it}^{off}, v_{it}^{on}, v_{it}^{off}, d_{it}^{on}, d_{it}^{off}, d_{it}^{B}, q_{it}^{on}, q_{it}^{off}\ge 0 \qquad \forall i\in M, t\in T \qquad (5.18)$$

Constraint 5.9 supplies production processes with necessary materials. The materials are drawn from either onsite warehouse or offsite warehouse to satisfy the total quantity needed by the production. Similar to the previous constraint, the total quantity of material i needed for production of other materials in period p is a summation of the order quantities that have been released prior to period p, times the usage rate of each item in the orders on the number of material i items. Then, the total number of material i items is distributed across multiple sub-period t in period p accordingly to the proportional term $\bar{\lambda}_{ijpt}$.

Constraint 5.10 balances the demand of customers for material i in sub-period t (i.e. $F_{ipt}D_{ip}$) and the quantity served by using a backlog d_{it}^{B} to carry the unserved demand to the next sub-period. Constraints 5.11 and 5.12 balance the onsite warehouse's inventory level and the offsite warehouse's inventory level with respect to the material flows, including movements into and out from the production facility (i.e. $\rho_{it}^{on}, \rho_{it}^{off}, g_{it}^{on}$ and g_{it}^{off}), deliveries to customers (i.e. d_{it}^{on} and d_{it}^{off}), movements between the warehouses (i.e. τ_{it}^{on} and τ_{it}^{off}), and raw material deliveries (i.e.v_{it}^{on} and v_{it}^{off}). Constraints 5.13 and 5.14 ensure that only raw materials can be purchased from suppliers, and are only delivered at the beginning of each time period. Constraints 5.16 and 5.17 set initial inventories to onsite and offsite warehouses, respectively. Finally, constraint 5.18 ensures that all variables can only assume positive values or zero.

5.4 Material Location Selection

In the previous section, an integrated material resource planning is formulated without restrictions on material-storage location. To observe the trade-off between the cost incurred by restricting material location and the convenience in locating storage locations for materials, a material-location selection model is developed by analyzing the material flow characteristics of each material type. The model uses a set of historical data to estimate potential material flow volumes with respect to each material's ideal flow plan. Section 5.4.1 explains the concept behind the construction of the proposed model. Then, the method is presented in section 5.4.2.

5.4.1 Flow-based Material Location Selection

The material location selection model presented in this section allocates materials to warehouses with respect to their ideal flows and average historical volumes, including the amount of demand served, the number of items delivered, and the number of items produced. With the assumption that warehouse storage space is unlimited, this study defines an ideal flow of a material as the flow that produces the lowest number of movements or touches until the material reaches the point of consumption. For example, an item of raw material needs at least two movements to bring it to the production plant; the first time is when the item is delivered at one of the two warehouses and the second time is when it is requested by production.

Each material's ideal flow defined in this study is illustrated and described as follows. For raw materials (Figure 5.5), once they are delivered at one of the two warehouses, they stay there until they are requested by the production plant. Since moving each item induces transportation cost, ideally when storage space is unlimited, materials will be delivered and stay in the warehouse where it has the lowest holding cost with respect to their transportation cost and length of stay. This can be explained in a mathematical relationship by assuming X and Y as inventory holding cost rates per item per period of a certain material stored onsite and offsite, respectively. D is the length of stay until the item is consumed by production. Storing the item offsite induces transportation cost C. If the item is stored onsite, then the total inventory holding cost will be XD. Comparing this to the case where the item is stored offsite, the total cost includes both transportation and inventory holding costs, resulting in $YD + C$. Depending on the difference in holding cost rates at both warehouses, length of stay and transportation cost, $(X - Y)D$ may be less or greater than C. This result is also applied to the flow of finished goods. Once an item of finished goods material is produced, it stays in one of the two warehouses until it is shipped to a customer or a distribution center (Figure 5.6).

In opposite to raw materials and finished goods, where items move in one direction, a semi-finished goods material may be moved from the production plant to a warehouse, from a warehouse back to the production plant, and from a warehouse to customers. Therefore, a semi-finished good can be a salable product, a work-in-process item or part that is required by other production. Figure 5.7 illustrates the ideal flow of semi-finished goods materials.

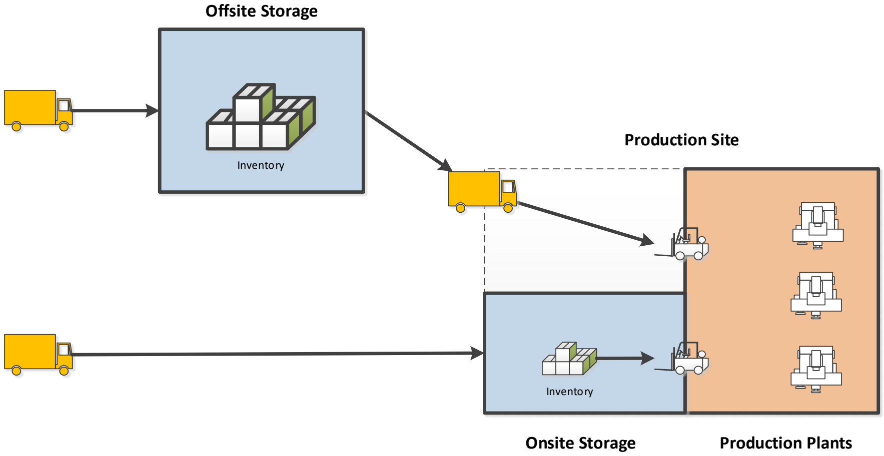

Figure 5.5 Ideal flow of raw materials

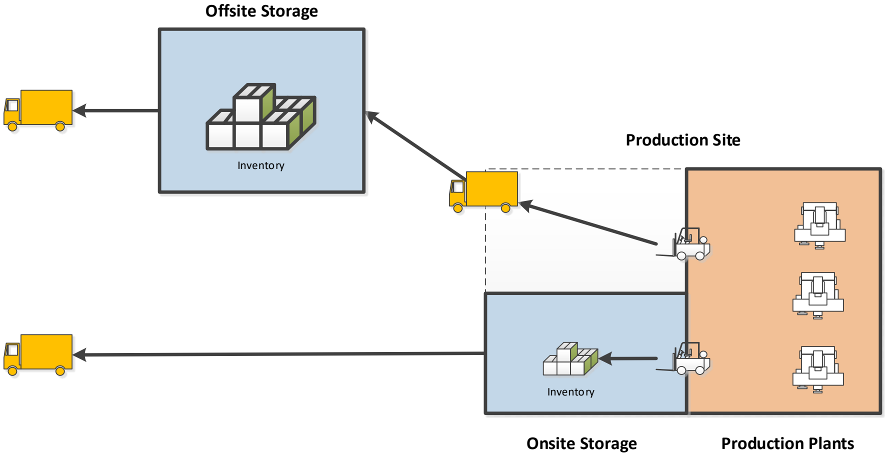

Figure 5.6 Ideal flow of finished goods materials

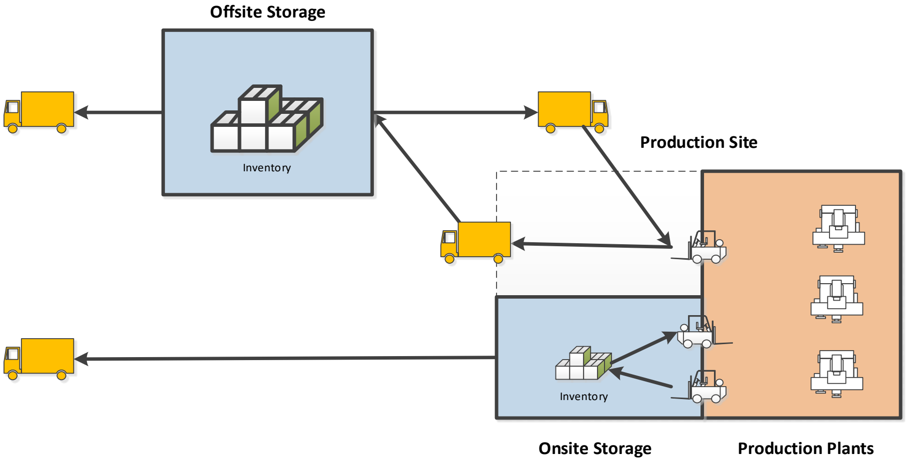

Figure 5.7 Ideal flow of semi-finished goods materials

The material-location selection model presented in this section allocates materials based on their historical data about their average item quantities in each period used for different kinds of activities such as production requests, satisfying demand, and inventory holding. Their flow quantities are estimated with respect to their ideal-flow characteristics described above. Items that exceed the onsite warehouse's capacity are stored offsite.

In addition to the above information, the following assumptions are made:

- If a material is stored in both warehouses, the items that are stored offsite will be used first.
- If a material can be stored onsite, it will be stored onsite up to its onsite storage limit first.
- The items that are delivered from suppliers, or produced by the production plant are received at one of the warehouses first before being transferred to other locations.

The idea behind the flow-based material location selection model is to allocate materials to warehouses according to their average ideal flows as described above. That is, if a material is allowed to be stored onsite up to a certain limit, the remaining items will be stored offsite. The items that are sent to offsite storage result in transportation cost. For example, 20 items of raw material A are allowed to be stored onsite. Let assume that on average 50 items of this material are delivered in each time period. Since material A is allowed to be stored up to 20 items onsite, the remaining 30 items of material A have to be stored offsite and will eventually be transferred to the production plant.

Transporting these 30 items will then result in transportation cost. This idea is the same for finished goods materials in which the items that are produced from the production plant, but exceed their onsite storage limit, are sent to offsite storage.

For semi-finished goods materials, which are produced by the production plant and also used to serve demand and production of other materials, their production incoming flows and outgoing flows are considered separately as separate constraints, and then combined into one constraint in order to reduce the total number of constraints in the model. Section 5.4.2 provides the formulation that represents this idea.

5.4.2 Notation and Formulation

The definition of sets, parameters, and variables used in the model are given as follows:

Set:

T : set of time periods

M : set of materials

RAW : set of raw materials

SFG : set of semi-finished goods materials

FG : set of finished goods materials

Parameters:

C_i^T : transportation cost per item of material i.

C_i^{HO} : onsite inventory holding cost rate per item of material i.

C_i^{HF} : offsite inventory holding cost rate per item of material i.

$\bar{D}_{it}$: average number of material i demand served in period t.

$\bar{G}_{it}$: average number of material i produced in period t.

$\bar{I}_{it}$: average inventory level of material i in period t.

$\bar{R}_{it}$: average number of material i delivered in period t.

S_i : unit space required for storing an item of material i.

K : onsite storage capacity.

Variables:

h_{it}^{on} : number of material i items stored onsite in period t.

h_{it}^{off} : number of material i items stored offsite in period t.

x_{it} : number of material i items flowing between onsite and offsite storage in period t.

y_i : number of material i items allowed to be stored onsite.

The flow-based material location selection is formulated as follows Equation 5.19 to 5.27. The objective function 5.19 is the summation of transportation cost and inventory holding cost that are estimated to happen on average. Constraint 5.20 limits the number of items allowed to be stored onsite to be less than or equal to the onsite storage capacity. Constraints 5.21, 5.22 and 5.23 are numbers of items belonging to different kinds of materials, which have different material flow directions. The logic behind these three constraints and steps to derive them are given after the mathematical model.

In addition to the first four constraints, Constraint 5.24 spreads the average inventory to onsite and offsite storage. Constraints 5.25 and 5.26 limit the number of items that can be stored onsite to be less than the number of items produced and delivered. In addition, they ensure that onsite inventory cannot be more than the limit. Finally, constraint 5.27 is a positivity constraint.

$$\min \sum_{i\in M}\sum_{t\in T} x_{it}C_i^{T} + \sum_{i\in M}\sum_{t\in T} h_{it}^{off}C_i^{HF} + \sum_{i\in M}\sum_{t\in T} h_{it}^{on}C_i^{HO} \tag{5.19}$$

Subject to:

$$\sum_{i\in M} S_i y_i \le K \tag{5.20}$$

$$\bar{R}_{it} - y_i \le x_{it} \qquad \forall i \in RAW, t \in T \tag{5.21}$$

$$\bar{G}_{it} - y_i \le x_{it} \qquad \forall i \in FG, t \in T \tag{5.22}$$

$$2\bar{G}_{it} - \bar{D}_{it} - 2\, y_i \le x_{it} \qquad \forall i \in SFG, t \in T \tag{5.23}$$

$$\bar{I}_{it} = h_{it}^{on} + h_{it}^{off} \qquad \forall i \in M, t \in T \tag{5.24}$$

$$h_{it}^{on} \le y_i \le \max_{\mathrm{k}\in\mathrm{T}}(\,\bar{R}_{ik}) \qquad \forall i \in RAW, t \in T \tag{5.25}$$

$$h_{it}^{on} \le y_i \le \max_{\mathrm{k}\in\mathrm{T}}(\bar{G}_{ik}) \qquad \forall i \in M - RAW, t \in T \tag{5.26}$$

$$0 \le x_{it}, y_i, h_{it}^{on}, h_{it}^{off} \qquad \forall i \in M, t \in T \tag{5.27}$$

Constraint 5.21 is the number of material i items that will be transferred from offsite storage to the production plant. Since at most the number of items y_i can be stored onsite, the remaining number of $\bar{R}_{it} - y_i$ are stored offsite and will eventually be moved to the production plant for producing other materials. Similarly, constraint 5.22 is the number of material i items that will be transferred from the production plant to offsite storage. Constraint 5.23 is a total number of items of semi-finished goods i that will be transferred between onsite locations and offsite storage. It is derived from the following variables and constraints.

- x'_{it} is the number of material i items produced and then transferred to offsite storage in period t.
- x''_{it} is the number of material i items delivered from the production plant to offsite storage in period t.

$$\bar{G}_{it} - y_i \leq x'_{it} \qquad \forall i \in SFG, t \in T \qquad (5.28)$$

$$\bar{G}_{it} - \bar{D}_{it} - y_i \leq x''_{it} \qquad \forall i \in SFG, t \in T \qquad (5.29)$$

$$x'_{it} + x''_{it} = x_{it} \qquad \forall i \in SFG, t \in T \qquad (5.30)$$

$$0 \leq x'_{it}, x''_{it} \qquad \forall i \in SFG \qquad (5.31)$$

Constraint 5.28 follows the same logic as constraint 5.22 for the semi-finished goods produced by the production plant. Since semi-finished goods are used to serve customer demand, by assuming that the items stored offsite are used first, the number of material i items transferred to the production plant is the remaining quantity after serving the demand, $(\bar{G}_{it} - y_i) - \overline{D}_{it}$ in constraint 5.29. Combining constraints 5.28 to 5.30 then yields constraint 5.23.

5.5 Study Cases and Production Environment Assumptions

The proposed solution is a heuristic based approach which runs until certain criteria are satisfied, therefore, three different production system scenarios each with 30 demand cases are used to observe the performance of the approach. The production systems, including bill of materials and demands used to test the proposed models are randomly generated with the following assumptions.

Production Operations and Planning Horizon

A production planning horizon refers to the timeline in which production decisions are determined. The following assumptions are made for the production systems used in this study.

- The planning horizon consists of 12 time periods.
- Each period consists of 22 sub-periods.
- Materials are delivered at the beginning of each period.
- Demand is continuously served.
- A production process will not start until all materials and resources required by the process are available.
- Production processes are served on a first-come-first-serve (FCFS) basis.
- Production orders are released to the production system as an alternating sequence of different material orders.

Without loss of generality, since the simulation model is a separate module that provides a feedback to the optimization model, different production control policies such as using different batch sizes or applying the constant work-in-process policy (CONWIP) are implemented.

Materials

Three kinds of materials are considered, namely raw materials, semi-finished goods and finished goods. A cyclic dependency of material production, such as reverse engineering, is not allowed. The percentage composition of materials is as follows:

- 10% of materials are finished goods.
- 20% of materials are semi-finished goods.
- 70% of materials are raw materials.

In a production system that has a relatively high number of materials, the materials may need to be filtered for the ones with relatively high floor-space or weight requirements in order to reduce the problem size. In addition, some small and low cost materials can be acquired within a relatively short amount of time, such as screws, rings and general gaskets, and can be excluded from the model. To further reduce the number of materials used in the model, the materials that are frequently used together can be grouped and stored under one material identification.

Resources

Resources such as machines and tools are shared among different material production. The production of a material is comprised of multiple processes. Each process may require multiple resources to start its operations. The following resource assumptions are made:

- There is one unit of each resource.
- Each resource can serve one production process at a time.
- Resources are not released back to the resource pool until the process that seizes them is finished.

- Resource capacity is expressed as the amount of time available in a period.

Among different equipment tools, some may only be used with a particular material production, may have several alternatives, or may require relatively short processing time. The ones that are not shared among different lines of production or are unlikely to cause a bottleneck can be filtered out in order to limit the problem size.

Scenarios and Demand Case

A scenario refers to the production system environment (i.e. number of materials, number of resources, resource capacities, bill of materials, and resource usage rates in each production, etc.). In this study, three different scenarios are created with different numbers of materials and resources.

A demand case is a dataset of material demands occurring in a production planning horizon. Each of the three scenarios contains 40 demand cases. Ten of the forty cases are assumed to be historical data and reserved for creating material-location plans. The remaining 30 datasets are used to create production plans. Material demands are created as follows:

- Demands for a material in each period are randomly generated with the normal distribution function.
- The mean and standard deviation of a material's demand are randomly selected for each period with the uniform distribution function by supplying ranges for means and standard deviations.

In addition to the above assumptions, the backlog cost charged on each item of unserved demand is assumed to be very large, i.e. 100,000 monetary units, in order to force the production planning model to serve as much demand as possible. The cost is assumed to be the same for all materials in order to prevent the model from favoring one material over another. Table 5.1 summarizes the dataset used in the experiment.

Table 5.1 Test scenario summary

Scenario Component Counts	**Scenario 1**	**Scenario 2**	**Scenario 3**
Number of Raw Materials	35	70	350
Number of Semi-finished Materials	10	20	100
Number of Finished Materials	5	10	50
Number of Shared Resources	10	25	125
Warehouse Size (floor space unit)	5,000	10,000	10,000
Min Transportation Cost Range	2.08	2.04	2.00
Max Transportation Cost Range	4.00	3.99	4.00
Min Onsite Inventory Holding Cost Range	1.67	1.45	1.41
Max Onsite Inventory Holding Cost Rate	9.61	10.34	10.26
Min Offsite Inventory Holding Cost Range	1.72	1.70	1.68
Max Offsite Inventory Holding Cost Rate	5.39	5.25	5.49
Min Floor Space	13.49	13.44	13.34
Max Floor Space	25.82	26.23	26.32
Min Number of Production Processes	2	2	2
Max Number of Production Processes	10	10	10
Min Number of Required Materials	1	1	1
Max Number of Required Materials	16	14	14
Min Number of Required Materials in BOM	3	1	1
Max Number of Required Materials in BOM	41	61	183
Min Number of Required Resources	3	2	2
Max Number of Required Resources	9	13	16
Min Number of Required Resources in BOM	6	2	2
Max Number of Required Resources in BOM	10	25	122

In real cases, the type of random distributions may be determined from the historical data. For example, a random distribution of material A’s demand in January may be obtained by fitting multiple random distributions with the multiple historical demands of material A in January. Another approach is to use the forecasted demands estimated by sales and marketing teams, which may incorporate multiple factors such as market trends and economic inflation.

5.6 Results and Discussion

In this section, the production plans generated by the two-warehouse MRP model are compared with the single warehouse MRP model. The comparison is expressed as differences in transportation and inventory holding costs between the two models. In addition, the cost trade-off for the convenience in locating and allocating materials to storage is analyzed by comparing the results yield by the two-warehouse MRP model solved with and without material storage restrictions.

Because the single warehouse MRP only considers one warehouse, the resulting costs cannot be directly compared with the two-warehouse MRP that include the transportation cost. In order to compare them, the production plans generated by both models are applied back to the two-warehouse MRP, but with all of the production plan related constraints, such as material deliveries, material requests, and production outputs, replaced by the values generated in the plans. In other words, to evaluate the production plans, the two warehouse MRP is reduced to the network flow model similar to those presented in Chapter 4 where the amounts of materials scheduled to be produced and delivered are given by the production management team.

In summary, the comparisons are separated into three sections. Figure 5.8 summarizes the comparison strategy for the subsequent sections. In section 5.6.1, the two-warehouse MRP is compared with the single warehouse MRP with respect to the cost differences between the two models, where the negative cost difference signifies that the former yielded lower cost than the later. In section 5.6.2, the two-warehouse MRP is compared against itself when it allows materials to be stored in any of the two warehouses, and when the storage location of each material is restricted by the material location plan generated by the model in section 5.4. In section 5.6.3, a similar comparison to section 5.6.1 is performed, but for when the material location plan is created and used to restrict the locations of materials in both a single warehouse MRP and a two-warehouse MRP. In addition, it compares the changes in the cost differences (i.e. gap between the circle mark and square mark in Figure 5.8) between the two models with material location plan against the two models without material location plan. Finally, a discussion and summary of the results is given in section 5.6.4.

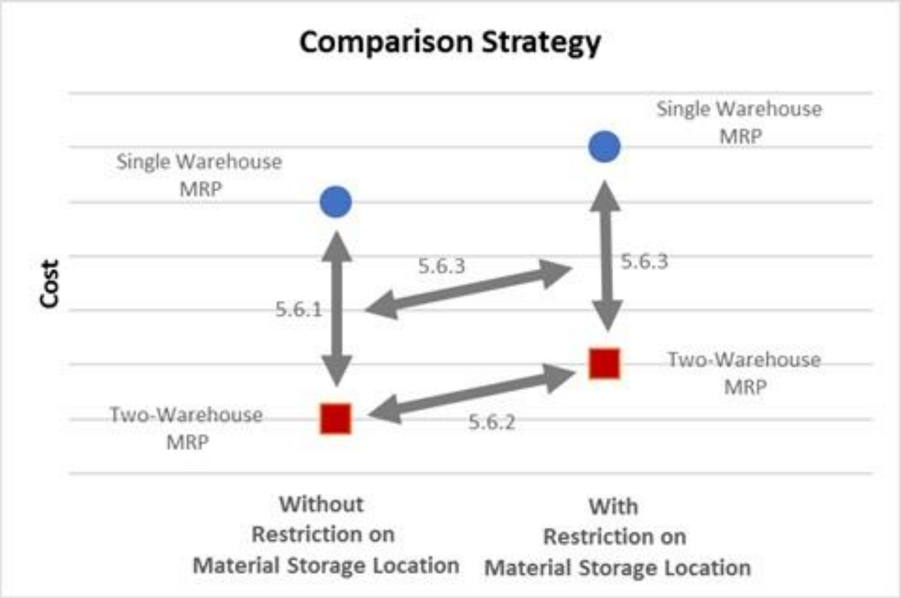

Figure 5.8 Comparison schemes that will be performed in the three subsequent sections.

5.6.1 Two Warehouse versus Single Warehouse Production Planning

The production plans generated by the two-warehouse and single warehouse material resource planning (MRP) models are run for all three production systems scenarios. Each scenario consists of 30 demand cases (i.e. datasets), resulting in 60 production plans for each scenario. Figure 5.9 illustrates boxplots of differences in the objective function values of both models. The objective function includes transportation cost, inventory holding cost and backlog cost. A negative value indicates that the two-warehouse MRP has a lower cost than the single warehouse MRP. The numerical results are given in Appendix.

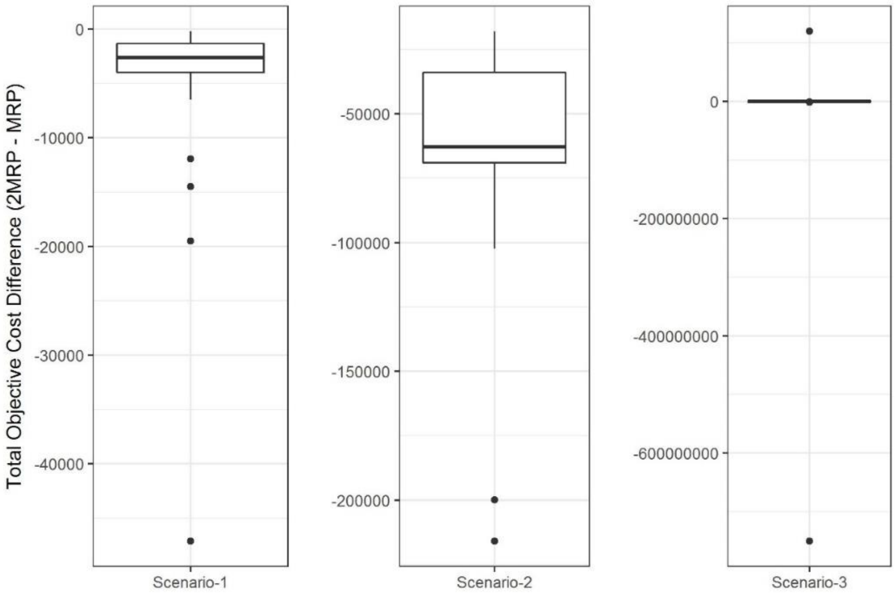

Figure 5.9 Differences in objective values calculated by subtracting the objective value yielded by the single warehouse MRP from the objective value yielded by the two-warehouse MRP.

According to Figure 5.9, 89 of 90 demand cases across scenario 1, 2 and 3 have lower total costs by applying the two warehouse MRP than by applying the single warehouse MRP. Each total cost consists of transportation cost, inventory holding cost and backlog cost. In order to analyze the effect of incorporating material flows and two warehouses into the production planning process, the results are filtered for the cases where both models yielded less than one item difference in the sum of the backlogs at the end of each period. The reason behind this filter is to exclude the cases where the two-warehouse MRP emphasized minimizing the backlog cost over transportation and inventory holding cost. Consequently, there are a total of 68 demand cases remaining; 27 cases for scenario 1, 27 cases for scenario 2, and 14 cases for scenario 3.

Figure 5.10 includes boxplots for the differences in the objective values without the backlog costs for the remaining demand cases. For two of the 68 demand cases, the two warehouse MRP produced production plans that resulted in higher total transportation and inventory holding costs than the single warehouse MRP. The differences range from (4,320) to 77,888 monetary units in scenario 1; (286,493) to (26,203) monetary units in scenario 2; and (285,070) to (44,004) monetary units in scenario 3. The differences in transportation cost and material inventory holding costs are plotted separately in Figure 5.11.

According to Figure 5.11, the two-warehouse MRP was able to achieve 66 of 68 cases that have lower total transportation and inventory holding cost. The differences in transportation costs range from (474) to 334 monetary units in scenario 1; (57) to (12,755) monetary units in scenario 2; and (2,431) to (13,590) monetary units in scenario 3. The differences in inventory holding costs range from (4,503) to 78,191 monetary units in scenario 1; (24,636) to (273,737) monetary units in scenario 2; and (40,362) to (276,224) monetary units in scenario 3.

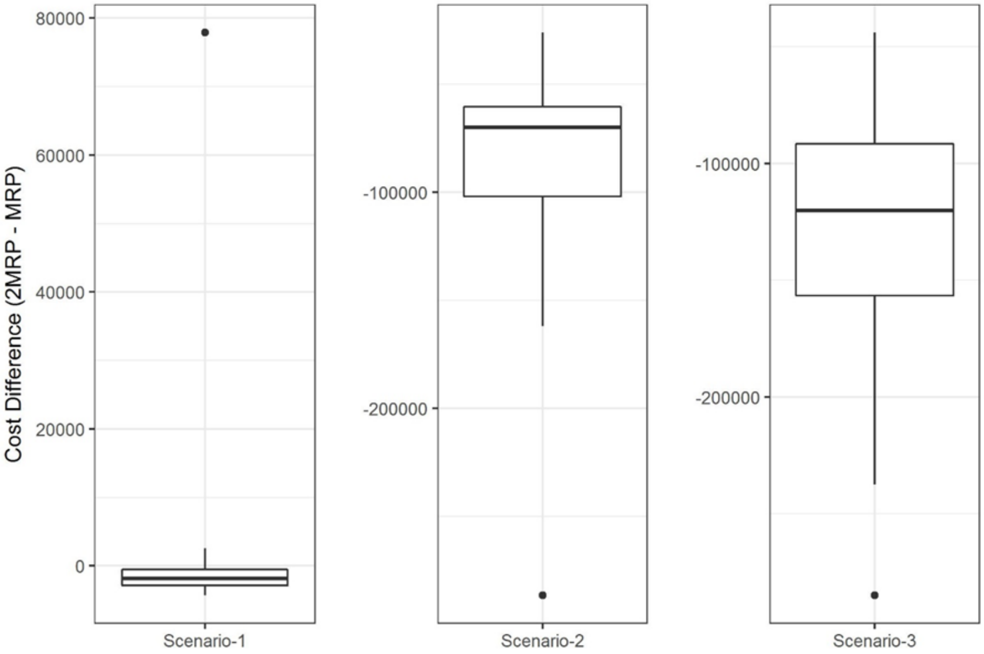

Figure 5.10 Differences in summation of transportation and inventory holding costs calculated by subtracting the summation yield by the single warehouse MRP from the summation yielded by the two-warehouse MRP

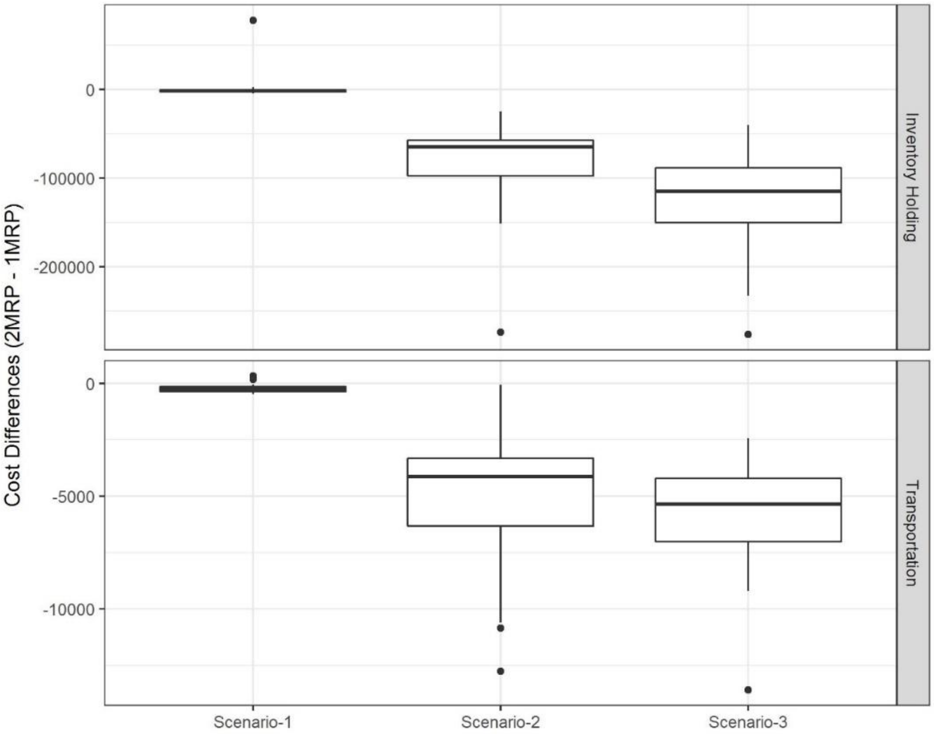

Figure 5.11 Differences in the summation separated by types of cost

The overall differences in inventory holding costs are higher than the differences in transportation costs. This is to be expected as the transportation cost is charged only when an item is moved, but the inventory holding cost is charged throughout the time that an item is in the system. With knowledge on the existing two warehouses and different inventory holding cost rates at each warehouse, the two warehouse MRP utilizes this information to create production plans that may yield lower transportation and inventory holding costs than the single MRP, which does not account for the existence of the rented warehouse. Note outliers exists in the plot since the solution approach is a heuristic, which runs until a certain criteria is achieved.

5.6.2 With versus Without Material Location Plan

The material location plan is added to the model when a production plan is being created. In other words, the location where each material can be stored is restricted by the material location plan generated by the model in section 5.4. Each material is associated with an onsite storage limit for where the material is allowed to be stored onsite. The results yielded by allowing items to be stored in any of the warehouses and yielded by restricting their storage locations are compared, in order to observe the tradeoff between the convenience in locating materials by using material location plans and the increase in transportation and inventory holding costs due to the restriction.

After filtering for the cases that resulted in less than one unit difference of backlogged items between the two models (i.e. two warehouse MRP with material location policy and two warehouse MRP without material location policy), 87 cases remained for the comparison, 30 cases from each of the first two scenarios and 27 cases from scenario 3. Figure 5.12 summarizes the cost increases using boxplots.

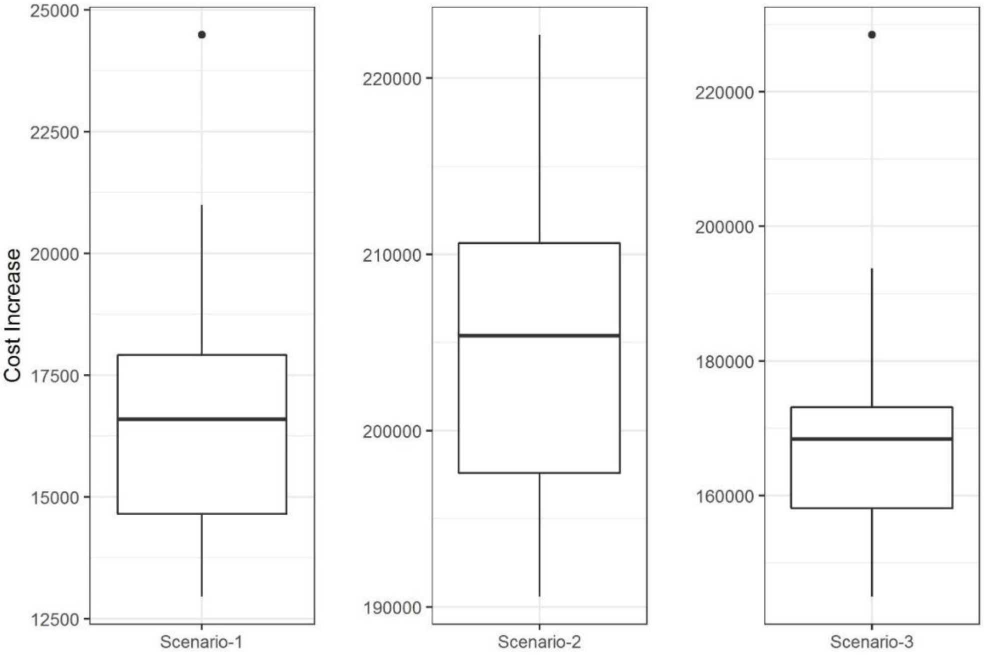

Figure 5.12 Increases in transportation and inventory holding cost summation yielded by the two-warehouse MRP after restricting where each material can be stored

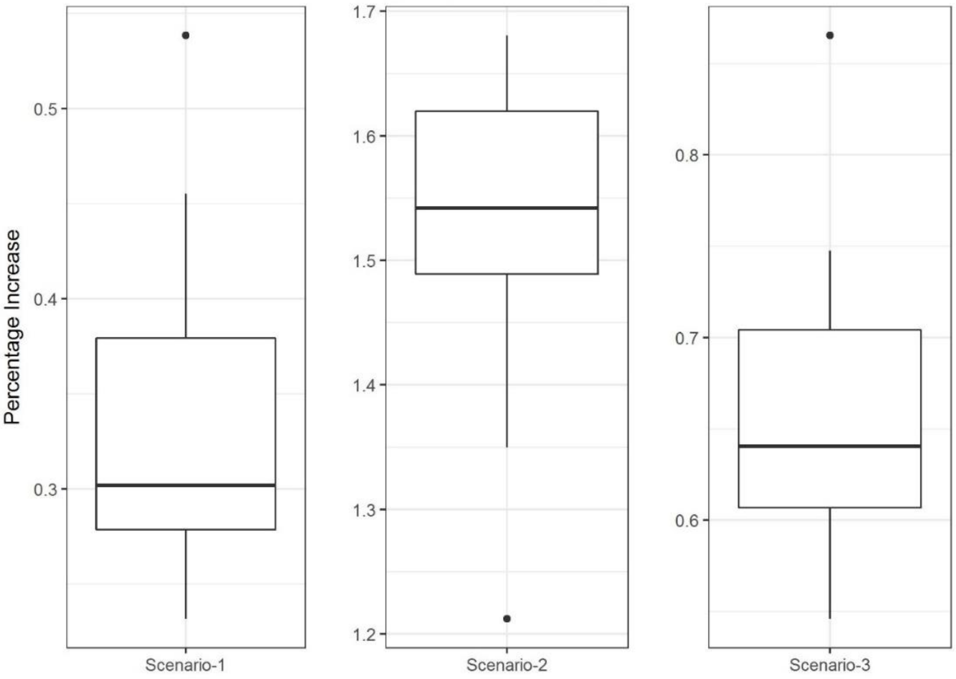

Figure 5.13 Percentage increase in summation of transportation and inventory holding cost with respect to the objective value without backlog cost.

The increases ranged from 12,955 to 24,487 monetary units in scenario 1; 190,588 to 222,460 monetary units in scenario 2; and 145,028 to 228,440 monetary units in scenario 3. The increases seem to diminish the cost differences shown in the previous comparison between two-warehouse MRP and single warehouse MRP. However, it provides an explicit material location plan to the warehouse management team. It also serves an operation guideline to assess to the situation in the warehouse, rather than solely relying on the judgement of an individual person on where to store items, as shown in Chapter 4. In addition, by comparing the relative cost increase to the total cost (Figure 5.13), applying material location contributes less than 2% increase in the total cost for every scenario tested.

5.6.3 Two-warehouse MRP with Material Location Plan versus Single MRP with Material Location Plan

The previous two comparisons (i.e. section 5.6.1 and section 5.6.2) have shown that the two-warehouse MRP yielded production plans with lower transportation and inventory holding costs than the single warehouse MRP, but the costs raised after the material location plans were used to restrict the locations where materials can be stored. In this section, the production plans generated by both models with material location plans are compared. The purpose of this comparison is to observe whether the cost saving benefit decreases if the single warehouse MRP also has material location plans restricting where each material can be stored.

After 90 cases were filtered for the cases where both models produced less than one unit difference in backlogged quantities, 68 cases remained for the comparison. These 68 cases are the same as the ones compared in section 5.6.1. Figure 5.14 compares the results of the single warehouse MRP against the two-warehouse MRP in form of the differences in total transportation and inventory holding costs. A negative value represents the case in which the two-warehouse MRP results in lower cost summation than the single warehouse MRP.

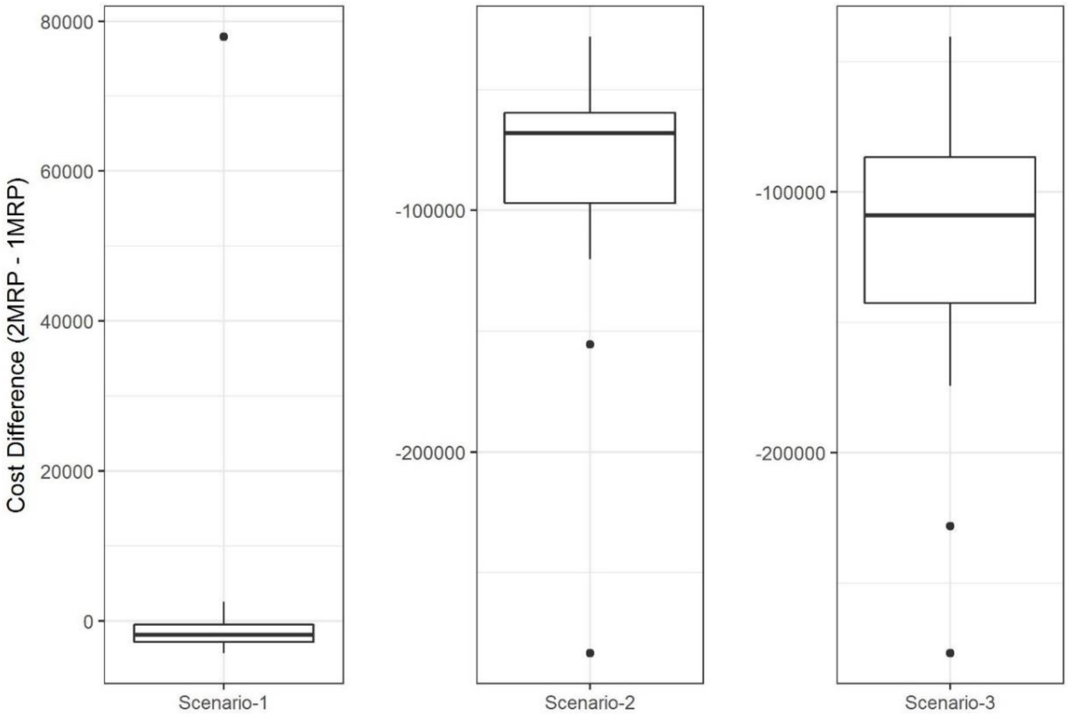

Figure 5.14 Differences in summation of transportation and inventory holding calculated by subtracting the summation yielded by the single warehouse MRP with restriction on material location from the summation yielded by the two-warehouse MRP with restriction on ma

According to Figure 5.14, using the two-warehouse MRP resulted in lower total transportation and inventory holding costs than the single warehouse MRP for 66 cases of 68 cases. The differences range from (4,313) to 2,577 monetary units in scenario 1; (27,960) to (283,373) monetary units in scenario 2; and (40,446) to (276,784) monetary units in scenario 3.

Comparing the cost differences between both models in both production planning schemes where the first scheme was presented in section 5.6.1 (i.e. without material location plan) and the other scheme is being presented here (i.e. with material location plans), the cost differences that are positive in section 5.6.1 remain positive in this section (i.e. 2 of 68 cases). Likewise, the cost differences that are negative in section 5.6.1 remain negative in this section (i.e. 66 of 68 cases). Figure 5.15 plots the changes (or gaps) of the cost differences from those presented in section 5.6.1 to those presented in this section (i.e. the cost differences of section 5.6.1 are used as reference -- $\text{Cost Difference}_{\text{section 5.6.3}} - \text{Cost Difference}_{\text{section 5.6.1}}$). A positive value means the cost saving potential obtained by using the two-warehouse MRP instead of the single-warehouse MRP decreases as each material storage location is restricted to certain locations.

For example, in one of the 27 cases in scenario 1, the cost difference yielded by the two-warehouse MRP and single warehouse MRP models is 77,888 monetary units when the material location plan is not applied. In the other case, when the material location plan is applied, this difference is 77,946 monetary units. The gap between these two cost differences are 77,946 minus 77,888, resulting in a 58 monetary unit difference, or equal to 0.07 percentage change. When both differences are positive, the positive difference (e.g. 58 units) between them means the gap between the total cost yielded by the two-warehouse MRP and the single warehouse MRP becomes larger with the material location plan applied. Note the positive cost difference (i.e. the two-warehouse MRP minus the single warehouse MRP) means the two-warehouse MRP yield a higher total inventory holding and transportation costs than the single warehouse.

Another example is when the cost differences are negative for both production planning with and without a material location plan. For one of the 27 cases in scenario 2, the cost difference is (286,493) without material location plan, and (283,373) with material location plan, resulting in a 3,120 monetary unit difference, or 1% change. When both differences are negative, the positive difference between them means the gap between the total cost yielded by the two-warehouse MRP and the single warehouse MRP becomes smaller when the material location plan applied. In other words, when the differences between the cost differences in this section and section 5.3.1 are positives, the cost saving advantage yielded by the two-warehouse MRP over the single warehouse MRP reduces.

According to Figure 5.15, by providing the material location plans for guiding the warehouse operations, the differences in total inventory holding and transportation costs between the two models change with the two-warehouse MRP being able to retain some of its cost saving advantage over the single warehouse MRP. The percent changes are 2.17%, 2.50% and 7.45% on average in scenario 1, 2 and 3, respectively.

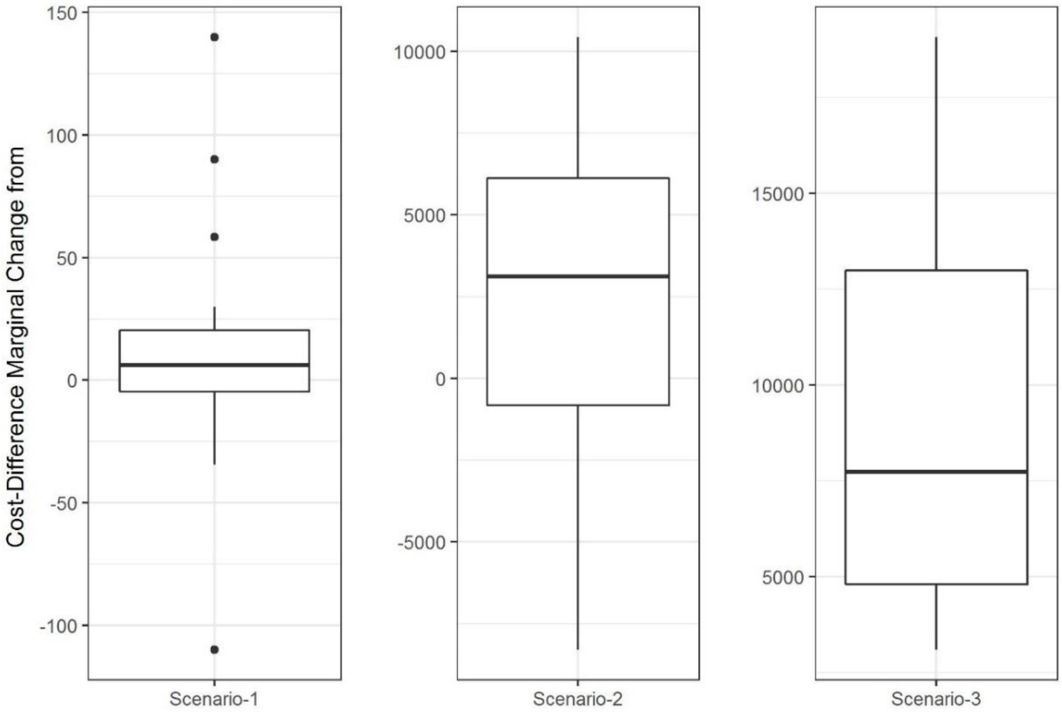

Figure 5.15 Changes in the gap between the total transportation and inventory holding costs yielded by the two-warehouse MRP and the single warehouse MRP

5.6.4 Result Discussion and Summary

According to the comparisons in section 5.6.1, in this experiment, using the two-warehouse MRP leads to higher cost savings (i.e. lower total cost) than the single warehouse MRP. In particular, the two-warehouse MRP yielded lower total inventory holding and transportation costs than the single warehouse MRP in 97% of the cases that both produced similar backlog quantities (i.e. less than one unit). Around 77%, 93% and 94% of the cost differences between the two models come from the savings in inventory holding cost.

When production planning considers the material location plans generated by the material location selection model proposed in section 5.4, the total inventory holding and transportation costs increased for all 90 cases. Consequently, the cost saving potential estimated in section 5.6.1 for two-warehouse MRP over the single warehouse MRP shrank. However, it provides a material location plan for guiding the warehouse operators for where to store and retrieve items, rather than assuming that the warehouse operators can determine these locations optimally like the models in section 5.6.1. Also, by comparing to the total cost including inventory and transportation costs associated with each demand case, the increases after the material location plans are less than 2%.

To evaluate whether considering the material location plan with the two-warehouse MRP will retain the cost saving potential over the single warehouse MRP, found in section 5.6.1, section 5.6.3 compares the case in which the material location plan is applied to both production planning schemes. The results showed the two-warehouse MRP still retains the cost saving benefit over the single warehouse MRP although the cost differences between both models shrank around 2%-8% on average for all three scenarios.

In this experiment, the material location model generates a material location plan by assuming the historical data about the material usage is available. In other words, it generates a material location plan in a retrospective manner where historical data is used to estimate material flow activities in the future. For different use cases, such as when the material demand is increasing during its demand lifecycle, the model can also be used with the forecasted data to dynamically generate the material location plan that corresponds to the forecast. However, using the model in this prospective manner may need be evaluated with the material relocation cost and with respect to the level of changes in demand.

5.7 Conclusion

In this chapter, the classic material resource planning model (MRP) that plans production by considering bills of materials and resource capacities was integrated with two warehouses and material flow constraints presented in Chapter 4. Due to the additional transportation cost induced by moving items in and out the production site and cost for the storage service provided by third-party logistics provider (3PL), the integration balances the space usage between the onsite warehouse owned by a company and the offsite warehouse space rented through 3PL. The models also allowed for observing the cost saving potential resulting from the integration. The results showed that considering the two warehouses and transportation cost in production planning can lead to a cost saving benefit in total transportation and inventory holding cost.

In addition to developing the two-warehouse MRP, a material location selection model was developed by analyzing each material type's ideal flow with respect to the flow constraints and inventory holding cost rates at both warehouses. As the locations where materials can be stored are restricted by the plan for the study cases, the transportation and inventory holding costs increased compared to allowing material to be stored in any warehouse. However, most of the cost saving from the single warehouse MRP is still retained. In addition, establishing a material location plan provides a guideline for managing the storage and locating materials.

Although using the two-warehouse MRP may lead to reduced transportation and inventory holding cost, solving the model for the production plan that can be followed by production can be challenging, since the production lead time is dependent on the system workload. Although the proposed approach uses an optimization model, the overall approach is still a heuristic. Different methods may replace the effective loading ratio to estimate the quantities of materials produced in each period after their order have been released. For example, a clearing function may be used to estimate production lead-time based on system workload (Karmarkar, 1989; Asmundsson et al., 2009). In addition, different production control policies based on different batch sizes and different order sequencing can be used in the simulation model to accommodate different production systems. The next chapter will show another application of the material location selection model. The model will be used to determine the additional space required in the onsite warehouse.

CHAPTER 6

WAREHOUSE CAPACITY EXPANSION: AN APPLICATION OF TWO-WAREHOUSE MRP AND TWO-WAREHOUSE MATERIAL LOCATION SELECTION MODELS

6.1 Introduction

The option to use a third-party (3PL) warehouse provides a company with quick access to additional storage space and helps a company absorb storage requirements variability due to changes in product demand. However, using a 3PL results in additional transportation cost to transfer items between the production site and third-party warehouse. In addition, the cost to store items in the warehouse and the differences in storage environment due to specialized technology, experience, and protection plan, may contribute to differences in the inventory holding costs between the owned warehouse and the rented warehouse. The question addressed in this chapter is how much offsite storage should be used if the owned warehouse can be expanded. In other words, this chapter serves as an application of the material location selection model and two-warehouse material resource planning (MRP) to determine the amount of additional storage space.

The previous research related to expanding a warehouse's storage capacity that was reviewed in Chapter 4 regarded the additional space as leased space, where excess inventory will be stored. Some of the existing models focus on determining item reordering quantities with the option of using the third-party warehouse as additional storage for excess inventory. In this context, the existing warehouse has a limit capacity, but may rent a third-party warehouse for additional storage space (Zhou and Yang, 2005; and Dem and Singh, 2012). Although this two-warehouse inventory control problem accounts for different inventory holding cost rates between each warehouse, it focuses on determining how many items should be ordered; therefore, how much of the rented space should be used while the onsite warehouse capacity remains unchanged.

Other models attempt to determine warehouse size considering a single type of material (i.e. aggregate unit) or multiple materials but with a single flow direction. A review of this group of models can be found in section 2.4 of Chapter 2. The details of the systems studied in these models vary based on their goal. For example, some focused on scheduling the time in which the warehouse storage capacity will be expanded (Cormier and Gunn, 1999), or setting up a rent or expansion plan that minimize the total cost (Cheng et al. 2009), as well as satisfying service level (Lee and Elsayed, 2007).

In this chapter, the material location selection model and the two-warehouse MRP presented in Chapter 5 are applied to solve the warehouse sizing problem for owned warehouse. This chapter is organized as follows. Section 6.2 presents the problem context in which the models will be applied and the modifications made on the material location selection models from Chapter 5. Section 6.3 presents the results and provides a discussion, and is followed by section 6.4 that concludes this chapter.

6.2 Problem and Experiment Description

The production system used in this chapter is a hypothetical scenario that is created using the same method for generating a bill-of-materials (BOM) and set of resources as in

Chapter 5. The BOM is assumed to contain no cyclic material dependency and requests multiple resources and materials for producing a unit of each material. Also, raw materials are assumed to be non-salable items and purchased from suppliers. The estimated construction cost rate is gathered from the websites that perform an estimation on warehouse construction cost and categorized cost components associated to a unit of warehouse floor space.

Assume a production company owns a warehouse with 5,000 floor space units. The warehouse is not only used to store the materials that are used in production, but also serves as temporary storage for finished goods before they are transferred to dedicate facilities such as distribution centers. In addition to owning a warehouse, the company rents additional storage space from a third-party logistics provider (3PL) to store excess inventory that cannot fit into the owned warehouse.

The system consists of 100 materials, including 10 finished goods materials, 20 semi-finished goods materials, and 70 raw materials. Materials are assumed to have different per-item inventory holding cost rates depending on which warehouse they are stored. To produce one unit (aka one item) of a material, raw materials go through successive processes where multiple resources are used to transform the materials into semi-finished goods and eventually finished goods. The production system’s components considered in the following experiments, like number of resources and inventory holding costs, are listed in Table 6.1. In this problem, a period refers to a monthly period which consists of 22 sub-periods, which represents a number of business/operational days for this particular company.

Table 6.1 Production system environment

System Component	Stat.
Number Raw	35.00
Number Semi-finished	10.00
Number Finished	5.00
Number Shared Resources	15.00
Warehouse Size (floor space unit)	5,000.00
Min Trans. Cost Range (per item)	\$2.00
Max Trans. Cost Range (per item)	\$3.98
Min Onsite Inventory Holding Cost Range (per item per sub-period)	\$0.35
Max Onsite Inventory Holding Cost Rate (per item per sub-period)	\$2.50
Min Offsite Inventory Holding Cost Range (per item per sub-period)	\$1.84
Max Offsite Inventory Holding Cost Rate (per item per sub-period)	\$5.14
Min Floor Space (square foot)	13.52
Max Floor Space (square foot)	25.77
Min Number Production Processes	2.00
Max Number Production Processes	5.00
Min Number Required Materials	1.00
Max Number Required Materials	7.00
Min Number Required Materials in BOM	1.00
Max Number Required Materials in BOM	17.00
Min Number Required Resources	1.00
Max Number Required Resources	8.00
Min Number Required Resources in BOM	1.00
Max Number Required Resources in BOM	19.00

The company is considering expanding its' warehouse after using it with a rented warehouse for several years. The investment will be made through loan with 4% annual interest rate over 25 years (i.e. http://www.bankrate.com/). The loan is amortized into multiple fixed payment amounts over the course of the loan. The amortization payment can be calculated by solving Equation 6.1 where A is a monthly payment, P is the loaned principal, r is an interest rate, and n is a number of payments.

$$A = P\frac{r(1+r)^n}{(1+r)^n - 1} \tag{6.1}$$

The company estimates the construction cost at \$105 per square foot (i.e. http://learn.rsmeans.com/rsmeans/models/warehouse/) with 4% interest rate over 25 years. By applying Equation 6.1, the periodic payment is about \$6.6 per square foot per year (i.e. or about \$0.55 per square foot per period, which is about \$0.025 per square foot per sub-period). The estimated operating cost, including labor (i.e. at \$7.5 per hour and 960 square feet coverage per day –or 72 pallets-- for a single person), equipment, utilities, insurance and tax, is about \$0.048 per square foot per sub-period. Thus, the estimated warehouse expansion cost rate is assumed to be \$1.75 per square foot per year over the 25-year plan. Note these costs are projected from https://www.cisco-eagle.com/blog/2012/09/24/the-cost-of-managing-a-skid-or-pallet/, and not meant to provide an accurate or up-to-date approximation, since the rate can vary greatly from one warehouse to another, depending on their efficiency in warehousing operations and construction. These numbers are only used to give a rough estimate in proportion of different operational component related costs for this case study.

To solve the warehouse expansion problem, the material location selection model presented in chapter 5 is applied. The model utilizes the past historical data on material flows. The historical material flow and warehouse usage data is obtained by solving the two-warehouse material resource planning model with randomly generated material demands. Ten demand cases, each with 12 periods that consist of 22 sub-periods each, are used to calculate average material flows needed by the material location selection model (i.e. number of materials flowing into the production plant, out from the production plant, received from suppliers and out to customers).

The additional variable z represents the amount of space added to the warehouse is added to the material location selection model in order to make a model capable of determining the warehouse size with respect to its usage. The variable is added to the objective function, resulting in equation 6.2 with a parameter E as the expansion cost rate. In addition, the warehouse capacity constraint is modified in constraint 6.3 to account for the increased space.

$$\min \sum_{i \in M} \sum_{t \in T} x_{it} C_i^T + \sum_{i \in M} \sum_{t \in T} h_{it}^{off} C_i^{HF} + \sum_{i \in M} \sum_{t \in T} h_{it}^{on} C_i^{HO} + Ez \quad (6.2)$$

$$\sum_{i \in M} S_i y_i \leq K + z \qquad (6.3)$$

Although the material location selection problem is solved for the optimal expansion size with respect to estimated/historical material flow, the model in the end yields only one warehouse size. With one single expansion size as an option to decide whether to build or not to build a warehouse the investment decision may not be justified, since building an infrastructure typically requires multiple kinds of warehouse design decisions, as well as analysis on competitive advantages that potentially help the company capture market demands and lower a production cost, such as quick demand response time and economy of scale (i.e. due to a low number of split orders, which may be charged for shipments separately). In order to support the investment decision, the two-warehouse material resource planning (MRP) model presented in Chapter 5 is solved with multiple warehouse sizes to provide a range of potential cost saving in warehouse operations. The sizes range from 5,000 to 40,000 square feet. For more details on different kinds of warehouse design decisions/problems, Baker and Canessa (2009) provides a comprehensive review of articles related to warehouse design problems and associated approaches to solve them.

In the experiment of this chapter, the distribution of each material's demand in each time period is assumed to be known through historical data or forecasting/marketing. Thirty demand cases estimated as next year demands are simulated and used in the two-warehouse MRP. A conservative estimation of cost saving, which assumes that the company will realize the same or at least the same amount of cost saving over the next 25 years, is performed by solving the 30 demand cases to obtain an average potential cost saving for the next year demand. Then, the payback period is calculated based on the total loan or investment that the company makes for adding additional storage space.

6.3 Results and Discussion

Solving the material location selection model results in 16,038 additional square feet, or 21,038 square feet in total. The estimated yearly expansion cost, including loan payment and additional operating cost is about $310,000 each year for the next 25 years (Table 6.2).

Table 6.2 Result from the two-warehouse material location selection

Additional space (Sq.ft.)	16,038
Construction cost loaned	$1,684,150
Additional yearly operating cost	$203,234
Fixed loan yearly payment	$107,806

To determine the cost saving potential from expanding the warehouse, the two-warehouse MRP was solved with 30 demand cases and 10 warehouse sizes, including the original size (i.e. 5,000 sq.ft.) and the size calculated by solving the material location selection model shown in Table 6.2 (i.e. 21,038 sq.ft.). The cost of the original warehouse size was compared against the different expansion cases. The comparison was done by subtracting the cost of the original size case from the cost for the expansion cases (i.e. original minus expanded). A positive difference means that expanding the warehouse resulted in a lower objective value, which is the summation of inventory holding cost, transportation cost, and backlog cost. Therefore, the difference is termed cost saving in this study.

The average of the cost savings over 30 demand cases is then calculated for each warehouse size case for calculating payback period, which are identified by simulating cash-flow of the warehouse in the next 25 years. As a conservative analysis, the same amounts of cost savings and expenses are assumed to realize yearly, but with an inflation rate of 2%. An example of the cash-flow for the warehouse with 21,038 square-feet space (i.e. 16,308 additional square feet) is displayed in Table 6.3.

Table 6.3 Cash flow of constructing and operating a warehouse with 21,038 square feet

End of Year	Amortized Construction Payment	Recurring Additional Operating Cost	Recurring Expansion Cost	Recurring Cost Saving from Inventory Holding and Transportation	Cash Flow	Discounted Cash Flow (Present Worth)	Cumulative Discounted Cash Flow
0	-	-	-	-	(1,684,150)	(1,684,150)	(1,684,150)
1	(107,806)	(207,298)	(315,104)	394,792	79,688	78,126	(1,606,025)
2	(107,806)	(211,444)	(319,250)	402,688	83,438	80,198	(1,525,827)
3	(107,806)	(215,673)	(323,479)	410,742	87,263	82,230	(1,443,597)
4	(107,806)	(219,987)	(327,792)	418,957	91,164	84,222	(1,359,375)
5	(107,806)	(224,386)	(332,192)	427,336	95,144	86,175	(1,273,201)
6	(107,806)	(228,874)	(336,680)	435,882	99,203	88,089	(1,185,112)
7	(107,806)	(233,451)	(341,257)	444,600	103,343	89,966	(1,095,145)
8	(107,806)	(238,120)	(345,926)	453,492	107,566	91,806	(1,003,339)
9	(107,806)	(242,883)	(350,689)	462,562	111,873	93,611	(909,729)
10	(107,806)	(247,741)	(355,546)	471,813	116,267	95,379	(814,349)
11	(107,806)	(252,695)	(360,501)	481,249	120,748	97,113	(717,236)
12	(107,806)	(257,749)	(365,555)	490,874	125,319	98,813	(618,423)
13	(107,806)	(262,904)	(370,710)	500,692	129,982	100,480	(517,942)
14	(107,806)	(268,162)	(375,968)	510,706	134,738	102,114	(415,828)
15	(107,806)	(273,526)	(381,331)	520,920	139,588	103,716	(312,112)
16	(107,806)	(278,996)	(386,802)	531,338	144,536	105,287	(206,825)
17	(107,806)	(284,576)	(392,382)	541,965	149,583	106,827	(99,998)
18	(107,806)	(290,268)	(398,073)	552,804	154,731	108,336	8,338
19	(107,806)	(296,073)	(403,879)	563,860	159,982	109,816	118,154
20	(107,806)	(301,994)	(409,800)	575,138	165,337	111,267	229,422
21	(107,806)	(308,034)	(415,840)	586,640	170,800	112,690	342,112
22	(107,806)	(314,195)	(422,001)	598,373	176,372	114,085	456,196
23	(107,806)	(320,479)	(428,285)	610,341	182,056	115,452	571,648
24	(107,806)	(326,888)	(434,694)	622,547	187,853	116,792	688,441
25	(107,806)	(333,426)	(441,232)	634,998	193,766	118,107	806,547

Base on Table 6.3, with the amortization, the company would pay $107,806 each year for 25 years to pay off the $1,684,150 loaned in year 0, which adds 16,308 square feet to the warehouse. As a result of the additional space, the company is expected to pay $203,234 additional operating cost each year with 2% inflation rate. According to the results of the two-warehouse MRP model (Table 6.4), this additional space is expected to save $387,051 on average each year with 2% inflation rate. By projecting the cash-flow over the 25-year timeframe, the investment would pay off and start to gain profit in 18 years. Table 6.4 summarizes the results of the two-warehouse MRP with payback periods for each warehouse size. In addition, Figure 6.1 plots the payback periods and average cost savings in inventory holding and transportation costs with associated warehouses sizes.

Table 6.4 Cost results from two-warehouse material resource planning model with associated warehouse sizes

Additional Space (Sq.ft.)	Construction Cost (Investment)	Yearly Fixed Payment	Yearly Additional Operating Cost	Average Yearly Inventory Holding and Transportation Cost Saving	Estimated Payback Period (years)
1,000	105,010	6,722	12,672	31,568	8.23
5,000	525,050	33,609	63,360	146,260	9.96
10,000	1,050,100	67,219	126,720	266,359	12.97
15,000	1,575,150	100,828	190,080	367,993	16.92
16,038	1,684,150	107,806	203,234	387,051	17.92
20,000	2,100,200	134,438	253,440	453,866	22.56
25,000	2,625,250	168,047	316,800	524,741	28.69
30,000	3,150,300	201,657	380,160	580,439	35.69
35,000	3,675,350	235,266	443,520	622,000	46.71

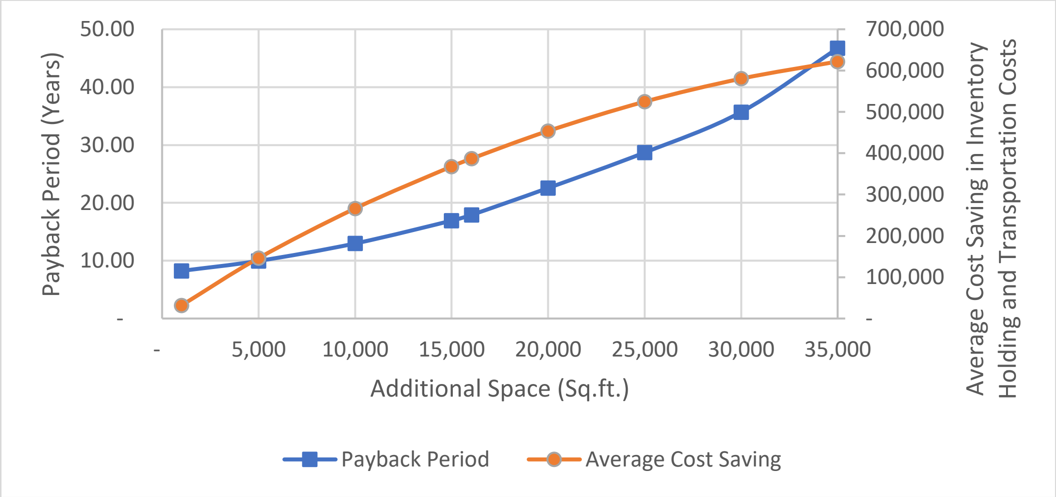

Figure 6.1 Plot of payback periods and cost saving in inventory holding transportation costs with associated warehouse sizes

According to Table 6.4 and Figure 6.1, the average cost saving over 25 years and the number of years in which the company will start gaining profit from the expansion increase non-linearly as the expansion size becomes larger. Based on Table 6.4, the expansion sizes of 25,000 square feet and beyond will not be able to generate cost saving fast enough to pay off the loans by the time they mature at the end of the 25th year. Also, the average cost saving increases with a decreasing rate, as the curve shows in Figure 6.1 which establishes the increasing side of the concave-like curve. Since the number of items in the system is limited by outside demand and some of materials have lower inventory holding cost rates at the offsite warehouse than the onsite warehouse, although the warehouse size increases, these materials will remain in the offsite storage and will not gain the cost saving benefit of being stored onsite.

In order to determine the warehouses size that will potentially provide the highest cost saving benefit over the next 25 years, the total expansion cost, including yearly loan payments and additional yearly operating costs, and the total cost saving in inventory holding and transportation costs were calculated and are summarized in Table 6.5 for each warehouse size. In the table, the differences between the total expansion cost and the total cost saving were also calculated to present the total amount of money that the company will gain or lose in the next 25 years from expanding the warehouse. Note these numbers are the present worth of costs and savings from the warehouse's estimated cash-flow, the same shown in Table 6.4. The differences are plotted in Figure 6.2 with a square tick-mark highlighting the warehouse size case determined by the two-warehouse material location selection model.

Table 6.5 Total present worth of cost and saving by the end of the 25-year time period.

Additional Space (Sq.ft.)	Present Worth of Total 25-Year Expansion Cost	Present Worth of Total 25-Year Inventory Holding and Transportation Cost Saving	Difference
1,000	448,035	789,198	341,163
5,000	2,240,173	3,656,489	1,416,316
10,000	4,480,346	6,658,977	2,178,631
15,000	6,720,520	9,199,826	2,479,306
16,038	7,185,580	9,676,277	2,490,698
20,000	8,960,693	11,346,655	2,385,962
25,000	11,200,866	13,118,526	1,917,660
30,000	13,441,039	14,510,965	1,069,926
35,000	15,681,213	15,550,012	(131,201)

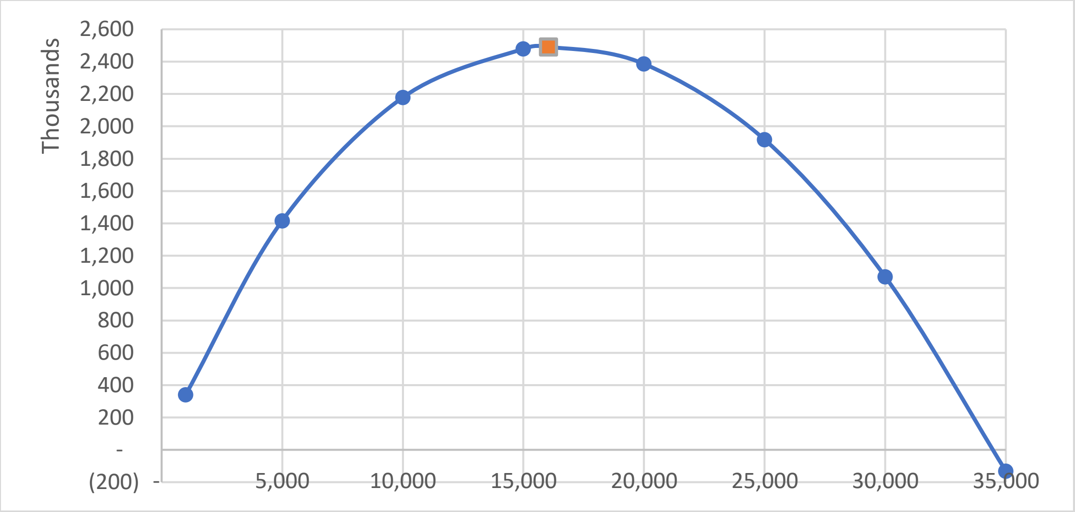

Figure 6.2 Total differences between expansion costs and savings in inventory holding and transportation costs

According to Table 6-5 and Figure 6-2, the case of 35,000 additional square feet does not provide enough total saving to offset the total expansion cost by the end of the 25th year, since the difference is negative. In addition, the case of 16,038 additional square feet determined by the two-warehouse material location selection model has the highest difference value, which means the company will gain the most profit in term of total cost saving in inventory holding and transportation costs by increasing its warehouse space by such amount. One important remark is that the loan payments that are part of the expansion cost will cease to exist once the loan matures at the end of the 25th year. This will result in higher differences between the expansion cost and the cost saving later on. That is, depending on how many years after the loan is paid off the company plans to keep using the warehouse, the total saving the company will get at the end of warehouse's life could be greater for one warehouse expansion case to another.

Another remark is that as the usage duration is lengthened, several kinds of variability such as warehouse maintenance frequency, demand fluctuation, change in the company's strategic plan, etc. could affect the estimated future saving amount. Therefore, depending on the stage of product lifecycle, the company might prefer to choose the warehouse size scenario that quickly realizes profit. In order to facilitate the decision in which an additional space amount is selected, the curve in Figure 6-2 could be used to view the effect of different warehouse sizes in term of cost saving in inventory holding and transportation costs.

6.4 Summary

In this chapter, the two-warehouse material resource planning (MRP) and material location selection models developed in Chapter 5 are applied to determine additional warehouse storage capacity. The chapter illustrates the potential of applying the models in a different application context. The material location selection is modified to solve for an optimal warehouse size. In addition, the two-warehouse MRP model is applied as a decision support tool that allows the user to create multiple scenarios for different warehouse sizes.

As an area of future work, the material location selection model may include a step-wise function for expansion cost in order to replicate a realistic cost incentive that a contractor may provide. For example, the additional operation cost that is a part of the expansion cost rate may not be linearly related to the expansion size. It could rather be a step-wise function similar to the work of Goh et al. (2001). Another example is when different kinds of material handling equipment, such as gravity flow rack, automated picking and retrieving system, and high capacity forklift, are deployed in order to increase the warehouse throughput rate or the area coverage per person. Another factor that could affect the operational cost is in the area of warehouse operation design, such as partitioning the warehouse into forward and reserve zones, using different storage assignment policies (i.e. random storage assignment versus dedicated storage assignment), and rack layout design. All of these factors are system dependent and can affect how the expansion cost is formulated and may be implemented in the simulation step of the two-warehouse MRP, in order to simulate the real production system. However, incorporating them could post a challenge to maintaining adaptability of the model and as such is beyond the scope of this research.

CHAPTER 7

SUMMARY, CONTRIBUTION AND FUTURE WORK

7.1 Summary

In this dissertation two problems related to the usage of two warehouses are introduced. In these problems one warehouse is owned by a company and the other is rented through a third-party logistics provider for additional storage space. The first problem allocates materials between the two warehouses while considering the transportation cost incurred from transferring materials in and out the production site, and the unique inventory holding cost rates for each material stored in each warehouse. The second problem attempts to integrate the two warehouses and material flow into the material resource planning model (MRP) for planning material productions.

Different research topics related to the use of two warehouses were reviewed in Chapter 2. The review showed that the use of two warehouses has been studied widely in the area of inventory control, where the rented warehouse is considered as an extension of the owned warehouse for storing excess inventory. This problem focuses on establishing the material ordering policy that minimizes the inventory holding and ordering costs while considering the benefit of economies of scale. In this context, either an aggregated inventory level or single flow direction materials (i.e. either from supplier to production plant or from production plant to customers) is considered, but how to determine the location that each material should be stored, along with consideration of the direction of material flow based on different kinds of materials (i.e. raw material, semi-finished goods and finished) has not been addressed in the literature.

The impact of allocating materials to different storage locations based on material types with respect to transportation and inventory holding cost was explored based on the material inventories and material flows of a real chemical manufacturer who supplies multiple chemical products to the global market. To extract its historical material flows and inventory levels from material movement transactions, an inventory rollback algorithm was developed in Chapter 3. The algorithm retrieves information regarding the locations each item has visited in the past and the inventory level of each warehouse by constructing a topological network graph and solving it for the longest path that represents the series of locations where each item visited. This analysis provides information such as the number of transported materials, the time duration for each material in storage, and the quantities of materials received from suppliers, demanded by production, and produced from production that was then used in Chapter 4.

In Chapter 4, multiple material location policies are formulated as mathematical optimization models to generate what-if scenarios for allocating materials based on the policies. The results, including transportation and inventory holding costs, obtained by solving the models were compared against the actual operations performed by the company. Although the results were affected by the seasonality of production demands, the comparisons showed that for this particular dataset the company would be able to reduce the cost from 15% to 40% by establishing a material-location policy for guiding the warehouse operators in managing the warehouse storage. This finding lead to the creation of a two-warehouse material location model and the integration of two warehouses and material flow activities with the production planning in Chapter 5.

In Chapter 5, a material location selection model was created by extending the network flow model presented in Chapter 4. In order to observe the effect of using two warehouses in the production system, and to evaluate the material location selection model, a two-warehouse material resource planning (MRP) model was developed by extending the methodology proposed by Kim and Kim (2001). Both models were solved with multiple demand cases that were randomly generated to represent changes in product demands. The results showed that the reduction in inventory holding cost accounted for more than half of the cost saving gained by incorporating the two-warehouses and material flows into the production planning. In addition, applying a material location plan that restricts material storage resulted in about 2% to 7.5% higher cost than the two-warehouse MRP without the storage restriction. However, using the material location plan is expected to provide a convenient means of managing the warehouse storage.

In addition to focusing on assigning materials into warehouses and incorporating the two warehouses and material flows into production planning, the potential for applying the models to determine the additional storage space that should be installed to reduce transportation and inventory holding costs was explored. In Chapter 6, the material location selection mode was modified to solve for additional storage space. Furthermore, the two-warehouse MRP was used as a decision support tool to generate multiple scenarios for different warehouse sizes, in order to observe the changes in inventory holding and transportation costs.

7.2 Contributions

The existence of third-party warehouses provides a manufacturer with quick access to material storage. However, using a 3PL induces transportation cost for bringing items in and out the production site. Although some third-party warehouses may be equipped with specialized equipment that reduces breakage or material deteriorating rates, the rent may offset such advantage and increase inventory holding cost, resulting in different holding cost between the two warehouses. Past studies on the use of a third-party warehouse with the owned warehouse are mainly concern with the amount of inventory that should be purchased and the amount of space that should be rented in order to take the advantage of scaled economy that allows a large volume of items to be purchased with lower per-unit cost than small volume purchase.

This study initiated the idea of a proper material location plan for allocating materials with consideration of material flow and understanding of how it is different for each of the three common material types, which are raw material, semi-finished goods, and finished goods. Chapter 5 has showed that without restricting storage location of each material, the transportation and inventory holding costs can be lower than restricting each material to a certain location. However, doing so means that the company has to be able to frequently determine and keep track of the optimal or relatively good material flow plans that minimize cost. As shown in Chapter 4 with an actual industrial's material flow situation where a material location plan was not present, the actual cost could be relatively high. In fact, prior to the analysis of the material flow, the manufacturer perceived a high volume of traffic between its' production site and the third-party warehouse, but was not certain of which materials had cause the negative impact. Also, in

Chapter 5, it has been shown that the increase in transportation and inventory holding cost ranged from 2 – 7.5% by restricting material locations, but this provides a solid plan for managing the storage location. The contribution made by this research to the advancement of warehouse management can be summarized as follows:

1. **Integration of multiple warehouses in to production system analysis**. This research incorporates multiple production warehouses as physical entities into the production system, which typically does not consider them as locations, but rather as an implicit storage space or storage capacity that is only used to limit the number of items in the system. This integration brings two kinds of hidden and activity-related costs into the analysis. That is, by considering them as physical entities, the material-dependent transportation cost and multi-direction material flow can be captured. In addition, location-dependent inventory holding cost rates of multiple materials can be simultaneously considered.
2. **Enhanced material flow foundation**. The research provided a base model that captures material flow and owned and rented warehouses, and can be further developed or extended to solve different production-and-warehouse related problems. It has been shown that the base model can be extended and applied to solve the material location selection, the production planning and the storage capacity expansion.
3. **Results confirmed by a real-world scenario**. In addition to exploring existing warehouse management research for the existence of third-party and owned production warehouses, and their joint usage, this work explored the

real-world cost saving benefit of considering both warehouses and material flow. A real manufacturer's data is used to analyze the cost saving potential that would be gained if the manufacturer has a systematic rule to assign materials into the warehouses. The result led to a new research area that, the authors believe, enhances the body of warehouse management research.

4. **New branch of warehouse management research**. The material location selection problem has been proposed as a new branch of warehouse management research. The problem aims to help warehouse managers efficiently utilize their warehouse space by establishing a material location plan that assists the managers in identifying item storage.
5. **Extension of MRP model to include material flow issues**. Last but not least, this study extended the traditional material resource planning model, which does not consider multiple storage location and transportation cost, by integrating the two warehouses and material flow. Then, it showed that both transportation and inventory holding costs can be lowered by allowing the production planning model to have knowledge of material and location dependent cost structure.

7.3 Future Work

This section describes potential areas of extending the developed methods and ideas behind them to increase their adaptability for different production systems or to solve different problems. The five different areas are listed here:

1. Impact study of operational level decision in production system on production planning;

2. Effect of different cost function in production planning;
3. Integration of warehouse operations with the two-warehouse capacity expansion problem;
4. Integration of warehouse design with the two-warehouse material location selection problem;
5. Integration of inventory control with the two-warehouse material location selection problem.

The developed two-warehouse material resource planning (MRP) approach mimics material production processes with a simulation model. Several assumptions are made regarding how production is operated, such as production service order while waiting for materials (e.g. first-in-first-out, shortest service time, etc.), production batch size, maintenance schedule, and material ordering cost. A study is needed to address the impact of these operational decisions on how the production plan is created in order to guide the selection and integration of the operational decisions with the production planning.

Using a different cost structure, such as step-wise function or economy of scale, for construction cost, transportation cost, and inventory holding cost, especially storage rent, is another improvement area that can make the two-warehouse MRP and the two-warehouse material location selection model applicable to different production systems whose cost components cannot be assumed a constant rate. For example, a third-party warehouse logistics provider may charge a company for each truck, rather than each item, moving in and out the production site. Also, the warehouse expansion cost may follow a step-wise function rather than a linear cost function. An example of the related capacity expansion work that considers space leasing cost as a step function is Goh et al., 2001.

Another potential future work is an integration of the warehouse expansion problem with warehouse operational decisions. Warehouse operational decisions such as storage assignment policy, pick-order batching, and routing may affect how the warehouse's floor space is used. For example, Petersen and Aase (2004) stated in their work that a random storage assignment policy that randomly assign items to storage often uses less space than a dedicated storage assignment policy that assigns items to specific pre-defined locations. An example of previous research that is related to the integrated warehouse expansion problem and the dedicated storage assignment policy is Lee and Elsayed, 2004.

In addition to integrating the two-warehouse warehouse expansion problem with warehouse operational decisions, integrating the problem with warehouse design issues such as warehouse partitioning, which splits a warehouse into forward and reserve areas, and warehouse dimensioning, which relates capacity to floor space. In this research, both warehouses are assumed to be black-boxes in which their internal functions are hidden; in other words, items are assumed to be stored in any location of the warehouses and retrieved from any warehouse where the items reside. However, in real practice, a warehouse can be partitioned into multiple areas or consist of multiple department (Gu et al. 2010b). For example, its storage area may be partitioned into a forward area where each material is stored with a smaller quantity than a bulk size, and reserve area where each material is stored in bulk size. Another example is that additional floor space may need to be translated into storage space rather than assuming that both types of space are the same. A comprehensive review on the warehouse design and operations problems can be found, as reference for future extension, in the works of Gu et al. (2007) and Gu et al. (2010a).

Last but not least, another future work involves extending the two-warehouse inventory control problem to include material flows to capture different material flow directions and incorporate multiple materials into the model. Most of the two-warehouse inventory control models reviewed in Chapter 2 consider materials as an aggregate volume or deals with a single material. By incorporating the material location selection plan into the inventory control model, the plan might be used to set up onsite storage limits for each material in the inventory control model.

APPENDIX A

The cost results of scenario 1, which consists of 50 materials, are shown in a table below. The model names in "Model" column refers to different experiment setups:

1. 2WH refers to solving the two-warehouse material resource planning (MRP);
2. 2WH+ML refers to solving the two-warehouse MRP with material location plans restricting material storage locations;
3. 2WH-ML refers to solving the two-warehouses MRP and then applying material location plans;
4. 1WH refers to solving the one warehouse MRP;
5. 1WH-ML refers to solving the one warehouse MRP and then applying material location plans.

Each setup was run with 30 demand cases. Three types of cost were shown in columns: transportation cost, inventory holding cost, and backlog cost.

Table A - 1 Results of scenario 1

Model	Case	Transportation	Inventory Holding	Backlog
2WH	1	425,567	4,214,423	3,295,768,974
2WH+ML	1	431,193	4,222,362	3,295,768,974
2WH-ML	1	431,203	4,222,353	3,295,768,974
1WH	1	425,664	4,217,405	3,295,769,915
1WH-ML	1	431,251	4,225,355	3,295,769,915
2WH	2	420,636	4,308,658	3,118,862,647
2WH+ML	2	427,395	4,315,914	3,118,862,647
2WH-ML	2	427,404	4,315,908	3,118,862,647
1WH	2	420,995	4,310,618	3,118,862,647
1WH-ML	2	427,683	4,317,805	3,118,862,647
2WH	3	517,937	5,266,736	3,219,911,971

2WH+ML	3	525,324	5,276,516	3,219,911,971
2WH-ML	3	525,345	5,276,500	3,219,911,971
1WH	3	515,003	5,214,665	3,220,014,116
1WH-ML	3	522,107	5,224,686	3,220,014,116
2WH	4	528,223	5,433,257	3,221,007,339
2WH+ML	4	533,292	5,442,620	3,221,007,339
2WH-ML	4	533,292	5,442,620	3,221,007,339
1WH	4	528,270	5,433,714	3,221,007,339
1WH-ML	4	533,321	5,443,091	3,221,007,339
2WH	5	431,558	4,096,895	3,395,508,979
2WH+ML	5	437,779	4,104,568	3,395,508,979
2WH-ML	5	437,790	4,104,558	3,395,508,979
1WH	5	431,764	4,098,123	3,395,508,979
1WH-ML	5	438,018	4,105,775	3,395,508,979
2WH	6	372,593	4,018,590	3,423,029,808
2WH+ML	6	378,612	4,032,565	3,423,029,808
2WH-ML	6	378,622	4,032,557	3,423,029,808
1WH	6	372,896	3,940,399	3,423,119,632
1WH-ML	6	378,928	3,954,303	3,423,119,632
2WH	7	506,021	5,149,561	3,164,867,207
2WH+ML	7	514,058	5,159,035	3,164,867,207
2WH-ML	7	514,069	5,159,026	3,164,867,207
1WH	7	506,345	5,151,589	3,164,867,207
1WH-ML	7	514,435	5,161,037	3,164,867,207
2WH	8	486,594	5,016,132	3,563,636,387
2WH+ML	8	495,892	5,027,318	3,563,636,387
2WH-ML	8	495,892	5,027,318	3,563,636,387
1WH	8	486,842	5,017,359	3,563,636,387
1WH-ML	8	496,149	5,028,514	3,563,636,387
2WH	9	502,466	5,597,320	3,122,892,810
2WH+ML	9	509,298	5,606,967	3,122,892,810
2WH-ML	9	509,299	5,606,966	3,122,892,810
1WH	9	502,269	5,594,936	3,122,901,881
1WH-ML	9	509,109	5,604,579	3,122,901,881
2WH	10	527,752	5,920,987	2,967,815,061
2WH+ML	10	535,974	5,927,704	2,967,815,061
2WH-ML	10	536,014	5,927,670	2,967,815,061
1WH	10	528,190	5,922,401	2,967,815,061
1WH-ML	10	536,331	5,929,191	2,967,815,061
2WH	11	553,295	5,618,016	3,621,689,233
2WH+ML	11	562,435	5,626,272	3,621,689,233
2WH-ML	11	562,427	5,626,384	3,621,689,233
1WH	11	553,408	5,619,292	3,621,689,233

1WH-ML	11	562,566	5,627,639	3,621,689,233
2WH	12	492,397	5,453,838	3,083,869,006
2WH+ML	12	499,415	5,462,792	3,083,869,006
2WH-ML	12	499,416	5,462,791	3,083,869,006
1WH	12	492,541	5,455,025	3,083,869,006
1WH-ML	12	499,510	5,464,018	3,083,869,006
2WH	13	526,184	5,336,807	3,482,926,521
2WH+ML	13	531,291	5,352,696	3,482,926,521
2WH-ML	13	531,310	5,352,680	3,482,926,521
1WH	13	525,850	5,341,137	3,482,926,521
1WH-ML	13	530,976	5,357,010	3,482,926,521
2WH	14	346,604	3,784,804	3,855,620,911
2WH+ML	14	355,046	3,792,122	3,855,620,911
2WH-ML	14	355,046	3,792,122	3,855,620,911
1WH	14	347,042	3,788,353	3,855,620,911
1WH-ML	14	355,477	3,795,670	3,855,620,911
2WH	15	498,103	4,910,983	3,151,568,530
2WH+ML	15	503,689	4,921,958	3,151,568,530
2WH-ML	15	503,706	4,921,945	3,151,568,530
1WH	15	498,378	4,913,467	3,151,568,530
1WH-ML	15	503,980	4,924,430	3,151,568,530
2WH	16	424,096	4,370,468	3,109,522,890
2WH+ML	16	429,438	4,378,081	3,109,522,890
2WH-ML	16	429,470	4,378,054	3,109,522,890
1WH	16	424,317	4,373,119	3,109,522,890
1WH-ML	16	429,684	4,380,714	3,109,522,890
2WH	17	410,775	4,266,952	3,344,794,603
2WH+ML	17	414,602	4,277,052	3,344,794,603
2WH-ML	17	414,608	4,277,048	3,344,794,603
1WH	17	400,080	4,144,990	3,344,941,747
1WH-ML	17	403,883	4,155,418	3,344,941,747
2WH	18	370,932	3,951,463	3,415,484,115
2WH+ML	18	375,433	3,966,197	3,415,484,115
2WH-ML	18	375,433	3,966,197	3,415,484,115
1WH	18	371,354	3,953,602	3,415,484,115
1WH-ML	18	375,850	3,968,336	3,415,484,115
2WH	19	430,331	4,422,611	3,433,448,847
2WH+ML	19	437,902	4,428,836	3,433,448,847
2WH-ML	19	437,925	4,428,819	3,433,448,847
1WH	19	430,758	4,424,969	3,433,448,847
1WH-ML	19	438,262	4,431,233	3,433,448,847
2WH	20	395,118	3,938,408	3,400,334,653
2WH+ML	20	399,409	3,950,236	3,400,334,653

2WH-ML	20	399,409	3,950,236	3,400,334,653
1WH	20	395,323	3,938,570	3,400,334,653
1WH-ML	20	399,613	3,950,379	3,400,334,653
2WH	21	381,963	4,166,429	3,519,033,139
2WH+ML	21	388,817	4,184,062	3,519,033,139
2WH-ML	21	388,817	4,184,063	3,519,033,139
1WH	21	382,104	4,166,489	3,519,033,139
1WH-ML	21	388,962	4,184,027	3,519,033,139
2WH	22	427,481	4,492,420	3,275,080,642
2WH+ML	22	435,256	4,503,595	3,275,080,642
2WH-ML	22	435,256	4,503,595	3,275,080,642
1WH	22	427,674	4,493,010	3,275,080,642
1WH-ML	22	435,451	4,504,177	3,275,080,642
2WH	23	472,031	4,916,222	3,273,273,291
2WH+ML	23	477,996	4,926,116	3,273,273,291
2WH-ML	23	478,007	4,926,107	3,273,273,291
1WH	23	472,505	4,918,397	3,273,273,291
1WH-ML	23	478,484	4,928,277	3,273,273,291
2WH	24	388,662	4,231,050	3,556,789,620
2WH+ML	24	394,459	4,244,629	3,556,789,620
2WH-ML	24	394,464	4,244,626	3,556,789,620
1WH	24	388,479	4,235,554	3,556,789,620
1WH-ML	24	394,293	4,249,108	3,556,789,620
2WH	25	569,787	6,342,268	2,998,527,029
2WH+ML	25	574,694	6,354,937	2,998,527,029
2WH-ML	25	574,709	6,354,925	2,998,527,029
1WH	25	570,124	6,344,898	2,998,527,029
1WH-ML	25	575,091	6,357,542	2,998,527,029
2WH	26	383,156	4,151,151	3,795,865,138
2WH+ML	26	388,764	4,162,457	3,795,865,138
2WH-ML	26	388,766	4,162,456	3,795,865,138
1WH	26	383,314	4,151,336	3,795,865,138
1WH-ML	26	388,924	4,162,638	3,795,865,138
2WH	27	479,622	5,044,615	3,006,388,120
2WH+ML	27	485,823	5,052,969	3,006,388,120
2WH-ML	27	485,836	5,052,959	3,006,388,120
1WH	27	479,908	5,047,462	3,006,388,120
1WH-ML	27	486,164	5,055,787	3,006,388,120
2WH	28	515,658	5,465,662	3,078,142,030
2WH+ML	28	522,258	5,475,672	3,078,142,030
2WH-ML	28	522,258	5,475,672	3,078,142,030
1WH	28	516,069	5,465,634	3,078,142,030
1WH-ML	28	522,519	5,475,770	3,078,142,030

2WH	29	345,393	4,052,707	3,861,179,593
2WH+ML	29	350,867	4,065,190	3,861,179,593
2WH-ML	29	350,879	4,065,179	3,861,179,593
1WH	29	345,635	4,052,957	3,861,179,593
1WH-ML	29	351,120	4,065,426	3,861,179,593
2WH	30	385,278	4,071,722	2,897,783,555
2WH+ML	30	393,985	4,080,789	2,897,783,555
2WH-ML	30	393,995	4,080,781	2,897,783,555
1WH	30	381,007	3,989,365	2,897,889,677
1WH-ML	30	390,003	3,998,105	2,897,889,677

APPENDIX B

This appendix lists the cost results of scenario 2 in Table B-1. Refer to Appendix A for definitions of columns.

Table B - 1 Results of scenario 2

Model	Case	Transportation	Inventory Holding	Backlog
2WH	1	1,144,224	11,850,295	2,728,774,270
2WH+ML	1	1,206,579	11,997,887	2,728,774,326
2WH-ML	1	1,206,191	12,005,106	2,728,774,270
1WH	1	1,155,061	12,001,320	2,728,678,477
1WH-ML	1	1,214,106	12,145,921	2,728,678,477
2WH	2	1,290,586	13,803,730	2,142,890,131
2WH+ML	2	1,370,878	13,927,203	2,142,891,216
2WH-ML	2	1,370,393	13,933,314	2,142,890,131
1WH	2	1,294,660	13,873,955	2,142,880,548
1WH-ML	2	1,372,729	13,990,978	2,142,880,548
2WH	3	1,170,623	11,722,018	2,616,178,971
2WH+ML	3	1,253,666	11,854,694	2,616,172,104
2WH-ML	3	1,253,223	11,850,884	2,616,178,971
1WH	3	1,174,032	11,823,428	2,616,139,856
1WH-ML	3	1,256,873	11,946,396	2,616,139,856
2WH	4	1,229,393	12,804,262	2,565,348,125
2WH+ML	4	1,298,947	12,938,996	2,565,346,150
2WH-ML	4	1,298,398	12,942,376	2,565,348,125
1WH	4	1,235,506	12,882,319	2,565,333,009
1WH-ML	4	1,302,007	13,013,719	2,565,333,009
2WH	5	1,063,294	11,232,491	2,519,314,282
2WH+ML	5	1,136,409	11,366,022	2,519,313,282
2WH-ML	5	1,136,084	11,366,296	2,519,314,282
1WH	5	1,069,825	11,325,176	2,519,245,321
1WH-ML	5	1,143,666	11,457,542	2,519,245,321
2WH	6	1,119,983	11,713,166	2,663,433,834
2WH+ML	6	1,195,595	11,844,871	2,663,433,834
2WH-ML	6	1,195,845	11,847,341	2,663,433,834
1WH	6	1,127,305	11,829,211	2,663,385,005
1WH-ML	6	1,200,217	11,960,505	2,663,385,005

2WH	7	1,243,961	12,414,514	2,385,441,103
2WH+ML	7	1,319,912	12,542,190	2,385,441,103
2WH-ML	7	1,320,040	12,543,375	2,385,441,103
1WH	7	1,247,039	12,474,164	2,385,441,103
1WH-ML	7	1,321,911	12,598,238	2,385,441,103
2WH	8	967,388	10,791,080	3,205,272,046
2WH+ML	8	1,022,634	10,926,422	3,205,272,045
2WH-ML	8	1,022,460	10,928,108	3,205,272,046
1WH	8	971,496	10,851,164	3,205,235,772
1WH-ML	8	1,026,095	10,990,864	3,205,235,772
2WH	9	1,141,407	12,256,596	2,666,417,838
2WH+ML	9	1,202,726	12,390,192	2,666,417,837
2WH-ML	9	1,203,457	12,391,692	2,666,417,838
1WH	9	1,156,623	12,416,212	2,666,310,716
1WH-ML	9	1,217,875	12,556,255	2,666,310,716
2WH	10	1,128,270	11,790,686	2,185,233,751
2WH+ML	10	1,206,195	11,906,377	2,185,233,749
2WH-ML	10	1,207,010	11,909,364	2,185,233,751
1WH	10	1,132,770	11,817,335	2,185,232,722
1WH-ML	10	1,209,121	11,938,353	2,185,232,722
2WH	11	1,169,346	12,100,909	2,499,544,585
2WH+ML	11	1,225,489	12,247,695	2,499,544,561
2WH-ML	11	1,225,642	12,248,101	2,499,544,585
1WH	11	1,170,349	12,157,246	2,499,527,718
1WH-ML	11	1,226,961	12,304,797	2,499,527,718
2WH	12	1,078,457	10,928,063	2,671,507,280
2WH+ML	12	1,148,686	11,055,855	2,671,508,492
2WH-ML	12	1,148,430	11,059,614	2,671,507,280
1WH	12	1,081,978	10,985,982	2,671,467,448
1WH-ML	12	1,149,122	11,117,875	2,671,467,448
2WH	13	1,169,275	12,201,974	2,401,218,739
2WH+ML	13	1,246,173	12,336,314	2,401,218,740
2WH-ML	13	1,245,933	12,338,042	2,401,218,739
1WH	13	1,174,815	12,270,164	2,401,218,749
1WH-ML	13	1,248,480	12,402,646	2,401,218,749
2WH	14	1,189,652	11,945,047	2,797,725,838
2WH+ML	14	1,262,894	12,086,205	2,797,725,871
2WH-ML	14	1,263,015	12,087,643	2,797,725,838
1WH	14	1,191,685	11,976,101	2,797,726,301
1WH-ML	14	1,263,552	12,113,508	2,797,726,301
2WH	15	1,071,338	11,903,886	2,877,234,950
2WH+ML	15	1,132,140	12,036,253	2,877,234,950
2WH-ML	15	1,132,207	12,039,971	2,877,234,950

1WH	15	1,079,834	12,010,139	2,877,193,847
1WH-ML	15	1,140,289	12,140,327	2,877,193,847
2WH	16	1,319,304	13,125,374	2,376,416,296
2WH+ML	16	1,403,100	13,261,415	2,376,416,290
2WH-ML	16	1,403,388	13,261,971	2,376,416,296
1WH	16	1,329,917	13,230,267	2,376,347,003
1WH-ML	16	1,414,275	13,367,614	2,376,347,003
2WH	17	1,156,972	12,501,375	2,110,925,584
2WH+ML	17	1,239,725	12,613,777	2,110,926,509
2WH-ML	17	1,239,195	12,620,211	2,110,925,584
1WH	17	1,161,160	12,546,585	2,110,915,677
1WH-ML	17	1,242,077	12,650,384	2,110,915,677
2WH	18	1,057,839	11,307,816	2,669,040,908
2WH+ML	18	1,127,065	11,434,385	2,669,040,908
2WH-ML	18	1,127,111	11,434,441	2,669,040,908
1WH	18	1,063,287	11,361,673	2,669,006,351
1WH-ML	18	1,131,957	11,490,245	2,669,006,351
2WH	19	1,136,251	11,300,077	2,681,672,069
2WH+ML	19	1,194,786	11,448,027	2,681,672,069
2WH-ML	19	1,194,650	11,450,265	2,681,672,069
1WH	19	1,142,852	11,363,480	2,681,665,090
1WH-ML	19	1,201,395	11,505,479	2,681,665,090
2WH	20	1,172,651	12,190,750	2,479,047,687
2WH+ML	20	1,243,034	12,314,445	2,479,048,077
2WH-ML	20	1,243,077	12,317,579	2,479,047,687
1WH	20	1,203,758	12,693,064	2,478,730,276
1WH-ML	20	1,269,184	12,816,799	2,478,730,276
2WH	21	1,478,831	15,238,380	1,932,115,824
2WH+ML	21	1,565,617	15,354,204	1,932,115,824
2WH-ML	21	1,565,363	15,356,083	1,932,115,824
1WH	21	1,484,842	15,297,221	1,932,107,047
1WH-ML	21	1,570,108	15,414,324	1,932,107,047
2WH	22	1,154,473	12,149,037	2,664,658,818
2WH+ML	22	1,229,835	12,284,335	2,664,667,256
2WH-ML	22	1,229,993	12,293,600	2,664,658,818
1WH	22	1,156,039	12,173,674	2,664,650,558
1WH-ML	22	1,231,331	12,317,338	2,664,650,558
2WH	23	1,233,509	12,866,720	2,322,257,544
2WH+ML	23	1,310,318	12,999,908	2,322,257,548
2WH-ML	23	1,310,354	13,001,598	2,322,257,544
1WH	23	1,236,099	12,902,570	2,322,246,126
1WH-ML	23	1,312,530	13,036,273	2,322,246,126
2WH	24	1,258,365	13,127,361	2,634,599,323

2WH+ML	24	1,326,484	13,273,541	2,634,600,177
2WH-ML	24	1,326,436	13,282,832	2,634,599,323
1WH	24	1,262,501	13,220,490	2,634,572,127
1WH-ML	24	1,329,826	13,358,409	2,634,572,127
2WH	25	1,056,307	11,561,820	2,816,786,160
2WH+ML	25	1,125,016	11,694,804	2,816,786,160
2WH-ML	25	1,124,798	11,697,485	2,816,786,160
1WH	25	1,060,378	11,626,117	2,816,783,592
1WH-ML	25	1,125,426	11,763,380	2,816,783,592
2WH	26	1,111,366	11,482,940	2,537,723,472
2WH+ML	26	1,172,932	11,629,502	2,537,717,992
2WH-ML	26	1,172,796	11,624,920	2,537,723,472
1WH	26	1,124,121	11,756,677	2,537,636,883
1WH-ML	26	1,182,460	11,903,347	2,537,636,883
2WH	27	1,248,364	12,365,263	2,413,397,263
2WH+ML	27	1,328,518	12,507,569	2,413,397,281
2WH-ML	27	1,328,924	12,511,048	2,413,397,263
1WH	27	1,248,421	12,430,088	2,413,394,414
1WH-ML	27	1,328,992	12,567,699	2,413,394,414
2WH	28	1,198,200	12,446,350	2,792,183,598
2WH+ML	28	1,274,826	12,580,398	2,792,183,473
2WH-ML	28	1,274,953	12,580,333	2,792,183,598
1WH	28	1,201,430	12,517,261	2,792,144,671
1WH-ML	28	1,276,487	12,648,527	2,792,144,671
2WH	29	1,280,081	12,957,306	1,965,683,087
2WH+ML	29	1,361,577	13,086,357	1,965,683,086
2WH-ML	29	1,362,257	13,087,366	1,965,683,087
1WH	29	1,295,701	13,137,966	1,965,555,581
1WH-ML	29	1,379,498	13,265,920	1,965,555,581
2WH	30	1,078,054	11,744,071	2,806,903,996
2WH+ML	30	1,143,978	11,875,612	2,806,903,995
2WH-ML	30	1,144,089	11,878,376	2,806,903,996
1WH	30	1,081,994	11,865,165	2,806,881,315
1WH-ML	30	1,144,953	11,992,513	2,806,881,315

APPENDIX C

This appendix lists the cost results of scenario 3 in Table C-1. Refer to Appendix A for column definitions.

Table C - 1 Results of scenario 3.

Model	Case	Transportation	Inventory Holding	Backlog
2WH	1	2,067,961	20,020,098	13,296,711,319
2WH+ML	1	2,158,482	20,086,129	13,296,711,466
2WH-ML	1	2,158,225	20,088,018	13,296,711,319
1WH	1	2,075,244	20,098,815	13,296,728,028
1WH-ML	1	2,164,279	20,159,139	13,296,728,028
2WH	2	2,307,901	23,444,260	13,450,113,208
2WH+ML	2	2,400,228	23,516,828	13,450,113,208
2WH-ML	2	2,400,371	23,518,754	13,450,113,208
1WH	2	2,297,253	23,327,381	13,450,478,251
1WH-ML	2	2,379,250	23,396,911	13,450,478,251
2WH	3	2,565,282	25,096,072	10,997,969,856
2WH+ML	3	2,685,704	25,142,622	10,997,971,203
2WH-ML	3	2,685,747	25,145,148	10,997,969,856
1WH	3	2,571,352	25,189,200	10,997,994,069
1WH-ML	3	2,687,177	25,229,761	10,997,994,069
2WH	4	2,889,155	28,041,438	12,097,909,189
2WH+ML	4	3,009,869	28,097,807	12,097,909,073
2WH-ML	4	3,010,512	28,099,715	12,097,909,189
1WH	4	2,892,760	28,221,963	12,098,161,452
1WH-ML	4	3,011,511	28,275,075	12,098,161,452
2WH	5	2,259,665	21,924,515	11,788,410,535
2WH+ML	5	2,361,099	21,980,537	11,788,410,535
2WH-ML	5	2,361,978	21,981,087	11,788,410,535
1WH	5	2,229,445	21,657,667	11,788,871,202
1WH-ML	5	2,327,511	21,712,424	11,788,871,202
2WH	6	2,266,263	23,094,759	14,321,469,460
2WH+ML	6	2,230,804	21,253,167	14,161,550,164
2WH-ML	6	2,364,275	23,161,475	14,321,469,460
1WH	6	1,819,748	18,489,413	15,077,116,751
1WH-ML	6	1,897,635	18,552,898	15,077,116,751
2WH	7	2,088,740	20,205,507	13,763,627,780

2WH+ML	7	2,172,054	20,286,630	13,763,625,069
2WH-ML	7	2,172,035	20,285,285	13,763,627,780
1WH	7	2,094,984	20,329,281	13,763,665,620
1WH-ML	7	2,171,223	20,398,393	13,763,665,620
2WH	8	2,712,546	26,236,898	13,039,961,613
2WH+ML	8	2,811,057	26,306,800	13,039,961,613
2WH-ML	8	2,811,212	26,307,580	13,039,961,613
1WH	8	2,709,788	26,351,567	13,040,073,302
1WH-ML	8	2,805,154	26,411,434	13,040,073,302
2WH	9	2,929,339	28,378,172	12,252,366,542
2WH+ML	9	3,041,569	28,436,862	12,252,366,579
2WH-ML	9	3,042,488	28,437,912	12,252,366,542
1WH	9	2,932,958	28,473,549	12,252,370,910
1WH-ML	9	3,044,104	28,526,805	12,252,370,910
2WH	10	2,115,420	20,799,889	12,553,722,922
2WH+ML	10	2,215,765	20,858,384	12,553,722,922
2WH-ML	10	2,216,105	20,859,292	12,553,722,922
1WH	10	2,120,897	20,917,352	12,553,777,879
1WH-ML	10	2,216,201	20,964,945	12,553,777,879
2WH	11	2,291,331	22,324,605	12,717,146,410
2WH+ML	11	2,393,998	22,384,982	12,717,147,222
2WH-ML	11	2,394,181	22,386,520	12,717,146,410
1WH	11	2,300,543	22,472,523	12,717,174,402
1WH-ML	11	2,389,173	22,532,964	12,717,174,402
2WH	12	1,787,155	18,041,565	14,202,185,628
2WH+ML	12	1,859,038	18,114,875	14,202,185,628
2WH-ML	12	1,859,379	18,115,446	14,202,185,628
1WH	12	1,796,000	18,317,790	14,202,205,266
1WH-ML	12	1,864,679	18,386,018	14,202,205,266
2WH	13	2,514,849	24,186,531	12,278,221,475
2WH+ML	13	2,609,876	24,261,734	12,278,220,995
2WH-ML	13	2,610,607	24,260,910	12,278,221,475
1WH	13	2,518,782	24,337,545	12,278,225,030
1WH-ML	13	2,605,780	24,406,974	12,278,225,030
2WH	14	2,278,759	22,075,388	13,866,776,697
2WH+ML	14	2,382,060	22,144,168	13,866,776,618
2WH-ML	14	2,380,576	22,146,497	13,866,776,697
1WH	14	2,283,879	22,307,851	13,866,717,751
1WH-ML	14	2,381,808	22,372,484	13,866,717,751
2WH	15	3,185,391	29,303,623	11,495,649,584
2WH+ML	15	3,327,872	29,354,876	11,495,649,340
2WH-ML	15	3,327,900	29,355,309	11,495,649,584
1WH	15	3,183,868	29,384,702	11,495,758,797

1WH-ML	15	3,322,688	29,423,239	11,495,758,797
2WH	16	1,608,585	14,523,060	14,335,080,044
2WH+ML	16	1,691,840	14,485,932	14,347,610,262
2WH-ML	16	1,701,229	14,581,411	14,335,080,044
1WH	16	1,885,814	19,346,078	14,210,416,916
1WH-ML	16	1,939,928	19,421,214	14,210,416,916
2WH	17	2,502,027	24,379,605	12,506,307,205
2WH+ML	17	2,614,483	24,476,992	12,506,553,166
2WH-ML	17	2,613,300	24,447,196	12,506,307,205
1WH	17	2,506,932	24,523,055	12,507,076,507
1WH-ML	17	2,610,295	24,576,705	12,507,076,507
2WH	18	2,034,180	20,176,586	12,878,558,593
2WH+ML	18	2,122,546	20,239,241	12,878,558,568
2WH-ML	18	2,122,623	20,239,921	12,878,558,593
1WH	18	2,036,612	20,263,233	12,878,605,638
1WH-ML	18	2,122,566	20,325,205	12,878,605,638
2WH	19	2,225,918	20,801,599	13,547,480,565
2WH+ML	19	2,318,061	20,873,288	13,547,480,489
2WH-ML	19	2,318,014	20,874,475	13,547,480,565
1WH	19	2,231,168	20,849,956	13,547,503,166
1WH-ML	19	2,319,469	20,921,530	13,547,503,166
2WH	20	2,646,189	25,017,807	12,392,149,318
2WH+ML	20	2,759,772	25,073,954	12,392,149,318
2WH-ML	20	2,759,756	25,075,147	12,392,149,318
1WH	20	2,647,355	25,016,808	12,392,271,235
1WH-ML	20	2,757,354	25,069,852	12,392,271,235
2WH	21	2,842,352	27,401,736	10,192,406,508
2WH+ML	21	2,960,628	27,465,486	10,192,406,508
2WH-ML	21	2,960,314	27,467,184	10,192,406,508
1WH	21	2,830,640	27,466,671	10,192,755,558
1WH-ML	21	2,943,412	27,519,111	10,192,755,558
2WH	22	2,589,265	25,328,982	11,174,127,802
2WH+ML	22	2,705,332	25,383,362	11,174,127,802
2WH-ML	22	2,706,100	25,383,345	11,174,127,802
1WH	22	2,577,090	25,152,436	11,174,462,114
1WH-ML	22	2,687,300	25,205,929	11,174,462,114
2WH	23	2,010,520	20,940,508	13,802,721,611
2WH+ML	23	2,093,696	21,002,454	13,802,723,334
2WH-ML	23	2,093,857	21,005,369	13,802,721,611
1WH	23	2,024,111	21,108,020	13,802,752,323
1WH-ML	23	2,093,687	21,176,845	13,802,752,323
2WH	24	2,896,813	28,323,298	12,031,389,182
2WH+ML	24	3,017,880	28,376,459	12,031,393,824

2WH-ML	24	3,017,929	28,381,626	12,031,389,182
1WH	24	2,773,527	27,063,281	12,033,569,236
1WH-ML	24	2,890,253	27,125,991	12,033,569,236
2WH	25	2,682,965	25,499,889	11,008,957,159
2WH+ML	25	2,808,625	25,558,642	11,008,957,144
2WH-ML	25	2,808,999	25,559,191	11,008,957,159
1WH	25	2,686,607	25,540,251	11,008,990,281
1WH-ML	25	2,811,687	25,596,027	11,008,990,281
2WH	26	2,647,628	26,071,262	11,824,026,654
2WH+ML	26	2,757,685	26,140,271	11,824,027,105
2WH-ML	26	2,758,251	26,142,430	11,824,026,654
1WH	26	2,640,762	26,046,363	11,824,248,336
1WH-ML	26	2,745,382	26,109,586	11,824,248,336
2WH	27	3,124,838	29,428,346	11,288,439,825
2WH+ML	27	3,247,941	29,533,684	11,288,398,076
2WH-ML	27	3,246,176	29,495,608	11,288,439,825
1WH	27	3,116,689	29,322,231	11,288,697,285
1WH-ML	27	3,236,595	29,387,275	11,288,697,285
2WH	28	1,491,754	15,267,245	14,657,496,076
2WH+ML	28	1,554,127	15,349,899	14,657,496,076
2WH-ML	28	1,554,326	15,350,131	14,657,496,076
1WH	28	1,497,079	15,435,005	14,659,206,064
1WH-ML	28	1,547,450	15,512,606	14,659,206,064
2WH	29	2,243,295	22,538,661	13,045,006,248
2WH+ML	29	2,335,816	22,597,345	13,045,009,237
2WH-ML	29	2,335,957	22,601,566	13,045,006,248
1WH	29	2,229,438	22,467,872	13,045,604,244
1WH-ML	29	2,321,525	22,526,332	13,045,604,244
2WH	30	2,126,420	20,714,173	12,084,016,846
2WH+ML	30	2,226,661	20,784,699	12,084,016,846
2WH-ML	30	2,226,904	20,786,150	12,084,016,846
1WH	30	2,131,439	20,826,604	12,084,021,996
1WH-ML	30	2,230,094	20,894,487	12,084,021,996

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