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Pull-based supply chain allocation for multi-product in multi-echelon distribution system

by

Pongchai Athikomrattanakul

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Major: Industrial Engineering

Program of Study Committee:
Pius J. Egbelu, Major Professor
Sarah Ryan
Timothy Van Voorhis
Clyde K. Walter
Ananda Weerasinghe

Iowa State University

Ames, Iowa

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P.O. Box 1346
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Graduate College
Iowa State University

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Pongchai Athikomrattanakul

has met the dissertation requirements of Iowa State University

Major Professor

For the Major Program

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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ABSTRACT

In today's highly competitive market environment, only companies with a highly efficient supply chain management, which integrates all decisions in various levels of planning and operations, can survive. These decisions must be coordinated and under the same goal, which is to minimize the total systemwide costs of the firm while products are manufactured and distributed to end-customers or retailers.

In this study, the focus is on a pull-based supply chain, customer demand driven, multiple products and multiple echelon distribution system consisting of *m* manufacturing centers, *n* distribution centers, and *p* retailers or customers. The objectives of this study can be categorized into two parts. The first objective is to present a general framework of the design and configuration of the supply chain network at strategic and tactical planning levels in a single-product and multi-product multi-echelon supply chain systems. The problems deal with determining the appropriate number, location, and size of each manufacturing facility and distribution center/warehouse that should be used within the logistics network. The second objective of the research is to present a methodology for using a pull-based supply chain system both for a single-product system and multi-product system at the operational planning level. The problems deal with determining which products customers will receive from each available manufacturing facility and distribution center, what production quantities of the products should be manufactured by a particular manufacturing facility, and what quantities of each product and ways of shipment should be used from manufacturing facilities to distribution centers and to customers.

Based on the nature of these large-scale mixed integer programming problems, decomposition heuristic algorithms based on relationships between primal and dual decompositions are developed. The mathematical models and the heuristic algorithms are then demonstrated and evaluated on several sets of randomly generated problems. Although the heuristic algorithms do not guarantee optimum solutions, their results of the test problems suggest that the heuristics are effective in solving fairly large problems with reasonable computational time. Furthermore, they produce superior performances as compared to the other techniques that are tested.

CHAPTER 1

INTRODUCTION

1.1 Introduction

In this study we consider a problem faced by many companies that try to integrate decisions along the supply chain system in order to maintain acceptable service level while minimizing the fixed costs of operating manufacturing centers, distribution centers (DCs), inventory holding costs at the DCs, and transportation costs between plants and DCs, and DCs and customers.

In today's global markets, each company must effectively manage its supply chain to meet the heightened expectations of customers and the short life cycles of products. Only companies that have efficient communication and transportation technologies along with a highly efficient supply chain management can survive in today's highly competitive market environment. To deal with this threat, companies need to improve their systemwide management policies within their supply chain to increase both the quality and service level of their products, and at the same time, also try to cut their systemwide costs. Companies' supply chain management, which integrates all decisions in the various levels of operations, must be implemented, so that their products with lower per-unit production costs are manufactured and distributed to end-customers or retailers at the right time, at the right quantities, and to the right locations. Supply chain management often involves all of a firm's activities and needs to be defined at a firm's strategic, tactical, and operational planning levels. Although each planning level requires different perspective and time horizon, it is important for each company to come up with an integrated plan, which supports and synchronizes all planning levels. Table 1.1 shows examples of decision making related to supply chain planning in each level according to Ballou (1999). The supply chain network usually consists of suppliers, manufacturers, warehouses or distribution centers, and retail outlets and sometime end customers, as well as raw materials, work-in-process inventory, and finished products that flow between the facilities.

All business interfaces within the supply chain must be considered as a whole since uncoordinated decisions could cause more investments and poor management that could lead to building up of inventory along the supply chain. Decisions on purchasing should not only be concerned with the low per unit costs for raw material, but also the production practices to achieve the lowest per-unit production costs. All decisions within business interfaces, or supply chain, must be made under the same goal, which is to minimize the total operating costs of the firm. Management should strive to minimize the total operating costs rather than the cost of each activity. Attempts to reduce the cost of individual activities may lead to increase in total cost. For example, consolidating finished goods inventory in a small number of distribution centers will reduce inventory carrying costs and warehousing costs but may lead to increase in freight expenses. On the other hand, savings associated with large volume purchases may increase inventory carrying cost. Therefore, reductions in one cost may result to increase in the costs of other activities. These uncoordinated decisions may end up leading to higher overall operating cost.

Type of Decision	Level of Decision		
	Strategic	**Tactical**	**Operational**
Location	Numbers of facilities, sizes, and locations.	Inventory positioning	Routing, expediting and dispatching
Transportation	Mode selection	Seasonal service mix	Replenishment quantities and timing
Order processing	Selecting and designing order entry system	Priority rules for customer orders	Expediting orders
Customer service	Setting standards	Setting pretransaction, transaction, and post transaction elements.	Providing the proper levels of service to meet customer needs.
Warehousing	Layout, site selection	Seasonal space choices	Order filling
Purchasing	Policies	Contracting, vender selection	Order releasing

Table 1.1 Examples of decision-making related to logistics planning in each level. (Ballou, 1999)

Regardless of the product design, marketing, and advertising issues, basically supply chain management can be divided into four major decision areas: customer service standards, facility location, inventory policy or deployment, and transportation mode selection and routing. The first priority in supply chain management is to set a proper customer service level since the level of service has a direct impact on the design of logistics systems. High levels of service normally use decentralized inventories at several locations and the use of, sometime, more expensive forms of transportation. Low levels of service generally require the use of less expensive forms of transportation and allows for centralized inventories at few locations. It is known that high levels of service mean high logistics costs.

Selecting the best number, location, sizes of facilities and stocking points are the other key areas in supply chain management, on which a company would need to make decisions. This selection process in literatures is called "Facility location problem". Generally facility location problem involves the determination of where to place the stocking points and the sourcing points in the logistics system. This also includes assigning market demand to each facility. Facility location problem includes all product movements and associated costs as they take place starting from plants all the way to end-customers or retailers. Finding the minimum assignment cost is the ultimate goal of this problem subject to monitoring the required service level.

The third key decision area in supply chain management is a company's inventory policy. A company needs to set an inventory policy, and this is usually either a push or a pull inventory policy. Push inventory refers to the produce-to-stock policy and pull inventory refers to the demand-driven policy. More details about push and pull inventory can be found in Chapter 4 of this manuscript. An effective inventory policy tries to reduce the number of stocking points throughout the supply chain. This will reduce the amount of inventory carried in the system, including total safety stocks. However, this reduced cost is a trade-off with higher transportation costs.

The last decision area in supply chain management is transport system selection and routing. Transportation selection and routing decision directly affects logistics decisions. The number, size and location of stocking points depend on the transportation policies of the company as much as on inventory policies. As the number of stocking points increases, fewer customers will be assigned to any one point and transportation costs will rise. The decisions basically relate to how to fill each customer's order from among the stocking points and which types of transportation modes must be used.

Other important and related issue in the supply chain is the distribution channel of a company. Distribution channels focus on the way the company structures its marketing function with customers. This marketing function depends usually on each company's marketing strategy, size, finance, and especially type of product. Channels of distribution affect the speed of delivery or delivery time, customer service, stocking points, and vitally the total logistics cost. For example a direct manufacturer-to-user channel usually gives management greater control over the performance of marketing functions, but distribution costs normally are higher. On the other hand, indirect channels have lower distribution costs, but the company marketing functions depend more on wholesalers or other external agencies. Figures 1.1 and 1.2 show examples of distribution channels both for consumer goods and industrial goods according to Lambert and Stock (1993).

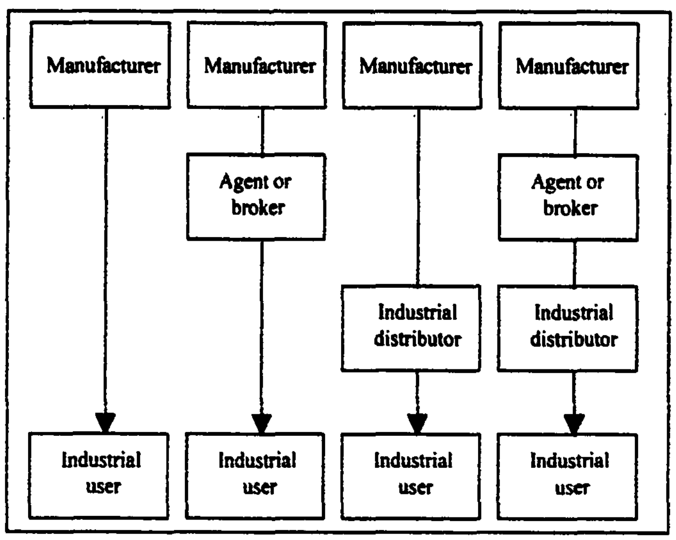


Figure 1.1 Channels of distribution for industrial goods (Lambert and Stock, 1993).

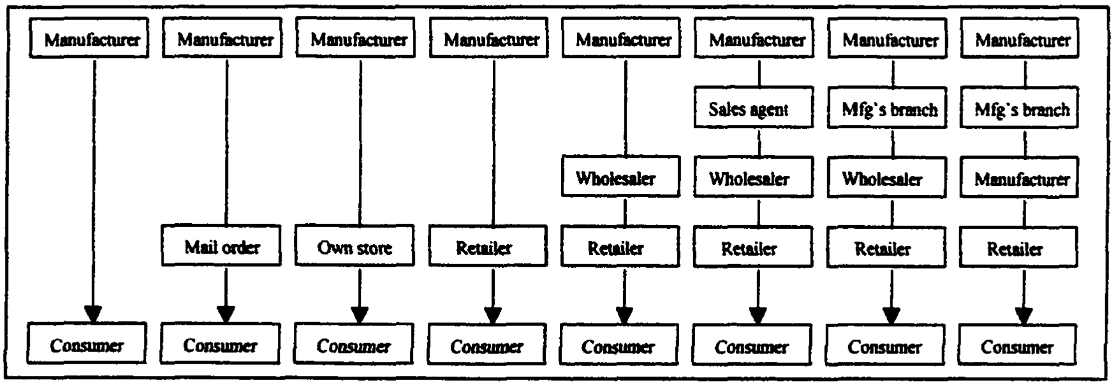


Figure 1.2 Channels of distribution for consumer goods (Lambert and Stock, 1993).

It is obvious that finding the right solution for these integrated decisions of the supply chain is challenging. Recently, researchers and practitioners have been increasing the attention placed on the performance, design, and analysis of these issues. Within manufacturing and production research, the supply chain concept grew largely out of two-stage multi-echelon inventory models, and it is important to note that considerable progress has been made in the design and analysis of two echelon system. More detail about this research area and its trend can be found in Beanmon (1998).

In this study a framework of two-echelon supply chain system with a single product and multi-products will be developed. A graphical illustration of the two-echelon supply chain system is as shown in Figure 1.3. The system consists of a set of multiple facilities of retailers or customers, warehouses or distribution centers, and production or manufacturing plants. In each echelon of the supply chain, all higher-level facilities can retrieve products from all lower-level facilities; such as at warehouses vs. retailers, all retailers can retrieve products from all warehouses.

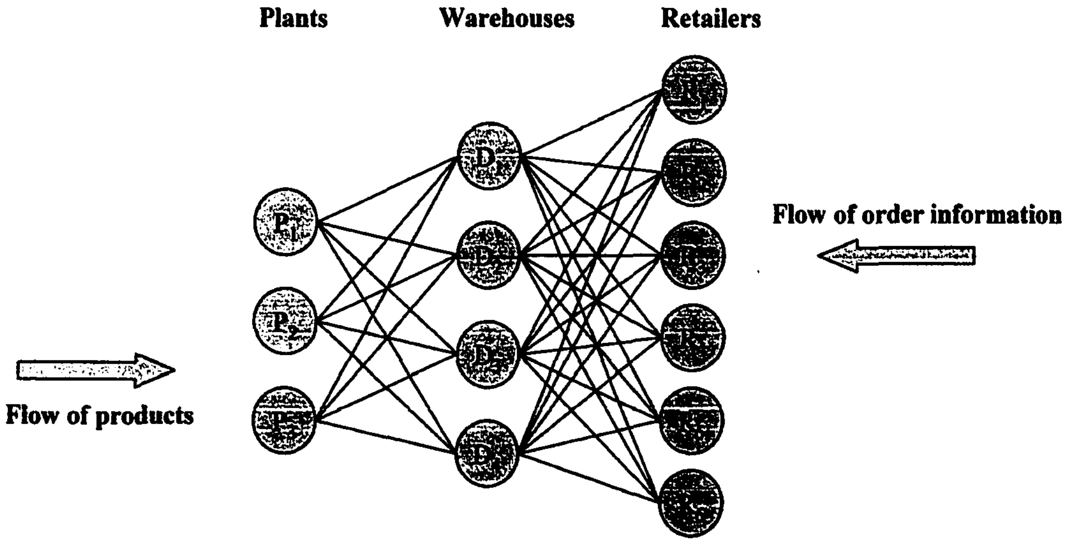


Figure 1.3. A two-echelon supply chain system consisting of three plants, four warehouses, and six retailers.

1.2 Objectives of Research

The integration of decisions in a supply chain network is the general purpose of this research. The objectives of this research can be categorized into two parts. The first objective of the research is to present a general framework of the design and configuration of a supply chain network at strategic and tactical planning levels in a single-product and multi-product multi-echelon supply chain systems. The problems deal with determining the appropriate number, location, and size of each manufacturing facility and distribution center/warehouse that should be used within the logistics network. This also includes determining which products will be produced by which manufacturing facilities and stored at which storage points. To solve this problem, two deterministic mathematical models are formulated: one for the single-product case and the other for the multi-product case. The objective for both models is the minimization of the total systemwide costs (which is discussed in detail, in Chapter 3). A decomposition heuristic algorithm is then developed to solve the models more efficiently, especially when dealing with a large-size supply chain system. The solutions obtained from these models provide the distribution network configuration of the supply chain system for each scenario.

The second objective of the research is to present a procedure for using a pull-based supply chain system both for a single-product system and multi-product system. The problems deal with determining which products customers will receive from each available manufacturing facility and distribution center, what production quantities of the products should be manufactured by a particular manufacturing facility, and what quantities of each product and ways of shipment should be used from manufacturing facilities to distribution centers and to customers. Beyond these common distribution and allocation tasks, the decisions of replenishing product quantities and the timing of the replenishment are also considered in the pull-based supply chain model by using the reorder point concept. A heuristic procedure is then developed to solve this pull-based supply chain problem. The outcome obtained from this problem provides a solution at operational level for order filling and inventory replenishment for a company.

1.3 Tasks to Be Performed

The following tasks will be undertaken in this study to realize the research objectives:

1) Present a framework of the supply chain system and define the total systemwide costs, which consists of all costs starting from the raw material stage through product delivery to customers.

2) Develop a mixed integer linear programming model to represent the supply chain network configurations, which includes all decision constraints such as the maximum capacity for each stocking point, maximum production capacity for each manufacturing facility, and the volume of customer demand at each demand point.
3) Develop a heuristic algorithm to select the best supply chain network configuration, the production plans, inventory stocking points, and transportation and distribution strategies, that will minimize the total systemwide costs.
4) Develop a heuristic procedure to determine the optimal customers' order filling and inventory replenishment decisions when a pull-based supply chain is applied.
5) Implement the heuristic algorithms on a personal computer.
6) Evaluate the heuristic computational performance and the results obtained from the pull-based supply chain system.

1.4 Research Assumptions

In pursuing the proposed research, the following assumptions are made:

1) Any plant can manufacture any product and supply to any distribution center.
2) Any distribution center can supply products to any customers.
3) The location and capacity of each candidate plant and distribution site is known and fixed. The candidate points are discrete and finite.
4) Average demand (units per year) for each demand point is known and is used for the network configuration design problem.
5) Actual demand (units per order) for each customer is known and is used for a pull-based supply chain problem.

6) In a pull-based supply chain system, each distribution center makes use of a continuous review (Q_i, r_i) policy, where Q_i is an order quantity for product i at each distribution center, and r_i is a reorder point for product i at each distribution center.

7) All distribution centers are resupplied only from the plants. That is, lateral supply among the facilities is not allowed. In practice, some lateral shipments do occur but on an informal basis so that we avoid to degrade the real system by not allowing lateral shipment to take place in our models.

1.5 Contributions of the Study

A framework of an integrated supply chain management system is presented so that all key decisions within the supply chain can be made toward the same goal, which is to minimize the total systemwide costs. By employing the supply chain model in this study, the following benefits can be derived:

1) The supply chain models developed can serve as tools for determining the number, size, and locations of all facilities within a supply chain. The models help to determine the whole logistics network and system configuration. This will give a measurable guideline for a firm's logistics planning both at the strategic and tactical levels. Especially, at the tactical levels, this will help the firm to adjust its inventory positioning, set priority rules for customer orders, and enter into purchasing contracts and select suppliers. Expanding the production capacity or stocking points are also the result of this study.

2) By applying a pull-based system and using fast information flow to transfer information about customer demands, all suppliers, stocking points or distribution centers, and manufacturers can fill customer order, supply raw materials or products, and refill inventory in each logistics levels in an economical fashion. This will lead to a decrease in lead times, in inventories throughout the supply chain, and in the performance variability in the system. It is known that a pull-based system gives a significant reduction in system inventory and system costs when compared to a push system. The heuristic procedure in the pull-based supply chain system will help a firm to deal with its logistics strategy and planning at operational level.
3) Most papers on supply chain system dealt with a single echelon system, which did not link together the decisions of production planning, inventory control, distribution, and logistics. In this study, all key decisions within the supply chain can be made at the time of fulfilling customers' orders.
4) The computational time of the heuristic algorithm in this study is exceptionally fast. Moreover, the algorithm is designed to deal with large scale problems while providing promising solutions as well.
5) The decomposition methodology developed in this study can be used in any types of multi-stage allocation or assignment problems such as capacitated facility location problems (CFL), and generalized assignment problems (GA) with some adjustments.

1.6 Organization of the Research

For ease of presentation and understanding by a reader, the remainder of this thesis is organized into five additional chapters. Chapter 2 reviews previous research, which have been done in areas related to the study. Chapter 3 defines the total systemwide supply chain costs in a supply chain and presents the framework of the supply chain network configuration. Two mix integer linear programming models, one for a single-product and another for multi-product cases, and their solution methodologies are also described in the chapter. Chapter 4 describes the concept of a pull-based supply chain system. The heuristic procedure to fill customers' orders and replenishment inventory both for the single-product and the multi-products cases are presented in the chapter. Chapter 5 employs numerical examples to test and demonstrate the effectiveness of the solution methodologies developed in Chapter 3, and 4. Finally, Chapter 6 presents the summary of results, conclusion, insights gained and possible extensions to the work presented in this study.

CHAPTER 2

SUPPLY CHAIN MANAGEMENT AND LITERATURE REVIEW

In the past few years, interest in supply chain management has grown dramatically. This interest has forced many firms to adjust and analyze their supply chains. In most cases, however, this has been done based on experience and intuition; very few analytical models or design tools have been used in this process, Simchi-Levi et al.(2000). In this chapter, we summarize the basics of supply chain management, BSCM, and some relevant research and issues that we refer to throughout this study.

2.1. Basics of Supply Chain Management.

2.1.1. Definition of Supply Chain Management

Supply chain management or logistics management refers to the management of the flow of goods from points-of-origin to points-of-consumption. In the past, a variety of names have been used according to Lambert and Stock (1993):

Physical distribution	Materials Management
Distribution	Materials logistics management
Distribution engineering	Logistics
Business logistics	Quick-response systems
Marketing logistics	Industrial logistics
Distribution logistics	

Nowadays, supply chain management and logistics management seem to be the most widely accepted term. The Council of Logistics Management, one of the largest and most prestigious groups of logistics professionals, provides the excellent definition of logistics management as following:

"Logistics management is the process of planning, implementing and controlling the efficient, cost effective flow and storage of raw material, in-process inventory, finished goods, and related information from point-of-origin to point-of-consumption for the purpose of conforming to customer requirements."

Another good, but similar, definition of supply chain management is defined by Simchi-levi et al. (2000) as following:

"Supply chain management is a set of approaches utilized to efficiently integrate suppliers, manufacturers, warehouse, and stores, so that merchandise is produced and distributed at the right quantities, to the right locations, and at the right time, in order to minimize systemwide costs while satisfying service."

Supply chain management or logistics management is a vital part of a firm's operation. Logistics is the third-largest source of cost of doing business for a typical firm after manufacturing and marketing. Efficient and effective management of the logistics function can have a substantial impact. Logistics cost is reduced, profitability is improved, and the level of customer service is increased. There are a number of key factors in supply chains, Arnold and Chapman (2000):

- A supply chain includes all activities and processes to supply a product or service to an end customer.
- Any number of companies can be linked in the supply chain.
- A customer can be a supplier to another customer so the total chain can have a number of supplier/customer relationships.

- While the distribution system can be direct from supplier to customer, it can contain a number of intermediaries (distributors) such as wholesalers, warehouses, and retailers.
- Product or services usually flow from supplier to customer and design and demand information usually flows from customer to supplier.

2.1.2. Integration along the Supply Chain

Basically, the integrated supply chain management concept refers to administering all supply chain activities as an integrated system. Integrating all distribution-related activities in the supply chain as mentioned in the previous section can reduce total operating costs of a company. Without this integrated approach, the costs to satisfy customer demand and expectations will be higher. A company must make a decision that coordinates all set of activities within the supply chain or business interfaces. The following are the list of critical business interfaces within the supply chain.

- Supplier-purchasing
- Purchasing-production
- Production-marketing
- Marketing-distribution
- Distribution-intermediary (wholesaler and/or retailer)
- Intermediary-customer/end-user

These business interfaces must be considered as a whole since uncoordinated decisions involving these activities could cause a build up of inventory along the supply chain. Now, the decisions of purchasing are not only concerning about the low per unit costs for raw material, but also need to consider the production to achieve the lowest per-unit production costs. All decisions within the business interfaces must be made under the same goal, which is minimize the inventory holding costs and logistics costs or total operating costs of the firm. Management should strive to minimize the total operating costs rather than the cost of each activity. Attempts to reduce the cost of individual activities may lead to increased total costs. For example, consolidating finished goods inventory in a small number of distribution centers will reduce inventory carrying costs and warehousing costs but may lead to an increase in freight expense or a lower sales volume. On the other hand, savings associated with large volume purchases may increase the inventory carrying costs. So, reductions in one cost may lead to increase in the costs of other activities. Effective supply chain management can be accomplished only by viewing logistics as an integrated system, and also minimizing its total operating cost subject to the company's customer service objectives.

2.1.3. Natures of Supply Chain Management Problems

Generally supply chain management problems involve the decision on how products are to move through the supply and distribution channels, and at the operational level, this includes decision on how to fill a recently received customer order, how to respond to a temporary transportation rate reduction, and how to route the current customer orders. Each day the supply chain system operates to move the products smoothly and efficiently through the channel. Basically the planning in supply chain management can be divided into four major decision areas: customer service standards, distribution network configuration, inventory policy or deployment, and transportation system selection and routing.

Customer service standards: the design of supply chain system greatly affects the level of customer service. Conversely, the level of customer service to be provided definitely impacts the design of supply chain systems. High levels of service normally use decentralized inventories at several locations and the use of, sometime, more expensive forms of transportations. Low levels of service generally require the use of less expensive forms of transportations and allow centralized inventories at few locations. It is known that high levels of service equates to high logistics costs. So, the first priority in supply chain planning must be the proper setting of customer service levels. Ballou (1999) suggests that effective supply chain planning should start with a survey of customer service needs and desires.

Distribution network configuration: distribution network decision involves how to place the stocking points and the sourcing points in the supply chain system. This also includes the number, location, and size of the facilities and assigning market demands to each facility. Generally distribution network problem includes all product movements and associated costs starting from plants/suppliers all the way to end customers. Finding the minimum assignment cost is the ultimate goal of distribution network planning. The following are the key questions in distribution network problem:

- What are the best number, location, and size of stocking points?
- Which plants/suppliers should serve which stocking points/facilities?
- Which products should be shipped directly from plants/suppliers to customers and which should be transshipped through the warehousing system?

Inventory policy: in general two strategies, push inventory and pull inventory, are involved in managing inventory throughout a supply chain. The push inventory strategy refers to a make-to-stock policy while a pull inventory policy refers to a demand-drive policy. More details on the push and pull inventory policies will be presented again in a later section. An effective inventory policy tries to reduce the number of stocking points throughout the supply chain system. This will reduce the amount of inventory carried in the system including the safety stocks. However, the cost reduction associated with inventory consolidation is in trade-off with higher transportation costs. With fewer stocking points, smaller outbound shipment sizes with higher shipping charges must be weighed against larger shipment sizes of inbound goods that travel through longer distances to the marketplace. Therefore, the distribution network decision must be sensitive to the inventory deployment and control policies used. This indicates that inventory policy directly affects the distribution network decision and the whole supply chain planning. The following are common questions related to inventory policy:

- What turnover ratio should be maintained?
- Which products should be maintained at which stocking points?
- What level of product availability should be maintained in inventory?
- Which method of inventory control is best?
- Should push or pull inventory strategies be used?

Transport selection and routing: transportation selection and routing decisions directly affect the supply chain decisions. The number, size and location of stocking points depend on the transportation policies of the company as much as inventory policies. As the number of stocking points increases, fewer customers will be assigned to any one point, the mode of transportation may change and this will affect the transportation cost.. The following are questions related to the transportation system selection and routing:

- Which customers should be served out of which stocking points?
- Which transportation types, truckload (TL) or less than truckload (LTL), should be assigned to which customers?
- Which modes of transportation, Rail, Truck, Air, Water, or Pipeline, should be used?

2.1.4. Important Issues in Efficient Supply Chain Planning

Cost trade-offs: supply chain planning needs to balance all conflicting costs such as transportation costs versus inventory costs, production costs versus distribution costs, and ultimately customer service costs versus all supply chain costs. All issues in the supply chain must be considered as a whole to avoid any suboptimal plans. Both facility location and distribution issues must be addressed at the same time, since output of facilities location decision is the input to the distribution system and are economically related to one another.

Consolidation: consolidation happens when small shipments are consolidated to form a large shipment to gain the economies of scale. For example, two or more customer orders might be combined with other customer orders received at other time periods to form a large shipment if possible. Consolidation strategy will lower average per-unit shipping costs. This also avoids shipping small quantities of items over long distances at high per-unit transport rate. In general, the concept of consolidation will be useful when the quantities shipped are small.

Postponement: the key idea of postponement is "to ship as much as you can as far as you can before committing to the end product." The final product processing and distribution are delayed until a customer order is received. This is done to avoid increasing total inventory level throughout the company logistics network and the possibility of obsolete stocks. Postponement can be classified into five types; Labeling, Packaging, Assembly, Manufacturing, and Time. For more details on these issues, the reader is referred to Zinn and Bowersox (1988).

Mixed strategy: a mixed strategy allows an optimal strategy to be established for separate product groups. Usually mixed strategy leads to lower costs than a single or global strategy. In general, single strategies can benefit from economies of scales and administrative simplicity, however they ineffectively perform when the product groups vary in terms of cube, weight, order size, sales volume, and customer service requirements. Examples of a mixed strategy include using of some public warehousing along with privately owned space, shipping product directly from the plants along with from the warehouses, and filling customer order from a single warehouse along with instances of shipping from multiple warehouses for some products.

2.1.5. Push-based versus Pull-based Supply Chain

Supply chain or logistics systems are normally categorized as push-based or pull-based systems. In a push-based supply chain system, long-term forecasts are used to determine a firm's production. On the other hand, in a pull-based supply chain system, production is demand driven, and therefore is directly related to actual customer demands instead of a forecast. With actual demands, a firm can decrease inventory both at the retail and the manufacturing levels, and also decrease the variability in the system due to lead-time reduction.

A significant reduction in system inventory level and costs make a pull-based system more superior to a push-based system. The trend today is toward pull-based system even though it is more difficult to implement than a push-based system. The succeeding sections summarize key concepts of these two supply chain systems.

2.1.5.1. Push-based Supply Chain System

In a push-based supply chain system, production decisions are based on long-term forecasts. Orders from the retailer's warehouses are used to forecast customer demand. This system is appropriate where production or purchase quantities exceed the short-term requirements of the inventories. However, a firm may have the problem of overstocking or excess inventory. The excess inventory could become obsolete, damaged, or nonfunctional because of age. High inventory leads to high inventory cost. A push-based system also produces larger and more variable production batches and this can impact the customer service levels, since the system has the inability to meet changing demand patterns. Moreover, a push-based supply chain increases transportation costs, heightens inventory levels and heightens manufacturing costs, due to inability to meet or react to changing market conditions. Figure 2.1 shows a push-based system.

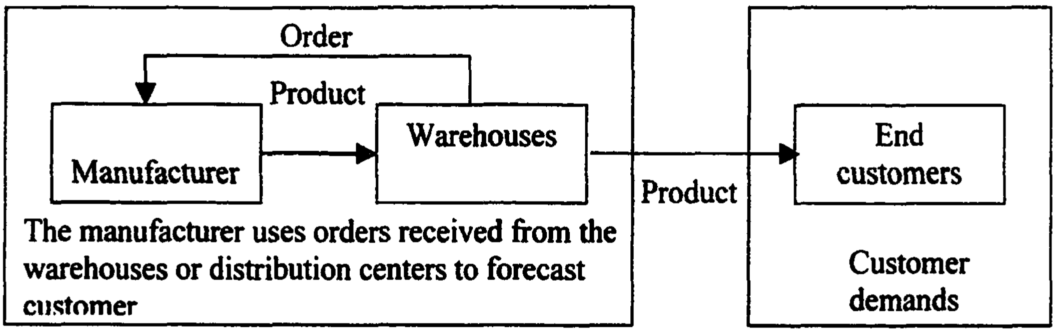
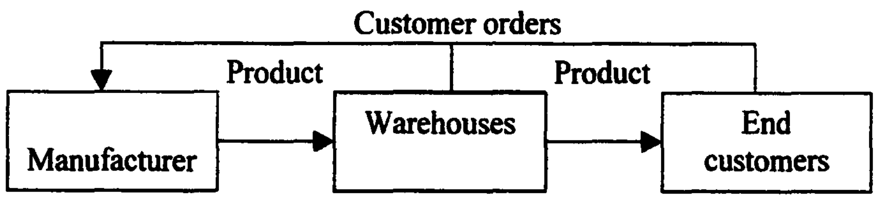


Figure 2.1 A push-based supply chain system.

2.1.5.2 Pull-based Supply Chain System

In pull-based supply chain system, actual customer demands rather than forecast are used in driving production or orders. In a pull-based system, the supply chain uses fast information flow to transfer information about customer demand to all stocking points and manufacturing facilities. This leads to a decrease in lead times, a decrease in inventories throughout the supply chain, and a decreasing in variability in the system. Pull-based system gives a significant reduction in system inventory and system costs. However, it is often difficult to implement when lead times are long. Furthermore, it is more difficult to take advantage of economies of scale in manufacturing and transportation since systems are not planned far ahead in time. To successfully apply a pull-based system, it is important to determine the procurement costs and lead time effects against inventory carrying costs. Since demand and lead time sometimes cannot be known with certainty, a firm must plan for the situation where not enough stock may be on hand to fill customer requests. In addition to the regular stock that is maintained for the purpose of meeting average demand and average lead time, an increment of inventory, safety stock, is added. Currently, there are two methods for controlling inventory in a pull-based system; 1) the reorder point method and 2) the period review method. Some firms also use a combination of these two. In this study, the reorder point method is used in the models developed. For more information about the reorder point method and inventory control, consult Ballou (1999). Figure 2.2 shows a pull-based supply chain system.



The supply chain uses fast information flow to transfer information about customer demands to all stocking points and manufacturers in order to fill customer orders, supply products and/or refill the inventory at each logistics level.

Figure2.2 A pull-based supply chain system

2.2. Literature Review

This section consists of a brief literature review of two streams of research that are associated with this study. The first stream of research concentrates on issues related to optimizing supply chain management. The second stream of research examines the issues related to determining the number and location of DCs in order to minimize the costs related to transportation and operating the DCs. The most fundamental form of this problem is known as the warehouse location problem and the location allocation problem. The nature of the problem usually focuses on solving a linear integer programming problem.

2.2.1 Supply Chain Management (SCM)

As mentioned above, a supply chain is an integrated manufacturing process wherein raw materials are converted into final products, then delivered to customers. Beamon (1998) classified SCM research into four categories: (1) deterministic analytical models, (2) stochastic analytical models, (3) economic models, and (4) simulation models. Regarding the focus of this study, literature review of SCM is limited to deterministic analytical problem since it is the branch most relevant here.

Cohen and Lee (1988) presented a model framework for integrated decisions throughout the supply chain. A heuristic optimization procedure was used to analyze inventories along the supply chain. They applied the heuristic to a problem that consisted of two finished products, three raw materials, one plant, two production lines within the plant, and three distribution centers. The distribution review period was one day and the production planning period consisted of 20 days.

Cohen and Moon (1990) proposed a constrained optimization model, called PILOT, to analyze the supply chain cost, and considered the additional problem of determining which manufacturing facilities and distribution centers should be opened. More specifically, Cohen and Moon considered a supply chain consisting of suppliers, manufacturing facilities, and distribution centers, and retailers. This system produced final products and intermediate products, using various types of raw materials. The objective function of the PILOT model was a cost function, consisting of fixed and variable production and transportation costs, subject to supply, capacity, assignment, demand, and raw material requirement constraints. Based on the results of their example, the authors concluded that there were a number of factors that might dominate supply chain costs under a variety of situations, and that transportation costs played a significant role in the overall costs of supply chain operations.

Cohen et al. (1990) developed an extensive multi-echelon logistics and inventory management system, called Optimizer, to provide customers with prompt and reliable service from IBM's National Service Division. The implementation of Optimizer had made it possible to make strategic changes to the configuration and control of the IBM parts distribution network. With Optimizer, IBM could simultaneously reduce inventory investment and operating costs and improve service levels.

Arntzen et al. (1995) developed a mixed integer programming model, called global supply chain model, (GSCM) that that incorporates multiple facilities, stages (echelons), time periods, and transportation modes. More specifically, the GSCM minimized a mixed function of: (1) activity days and (2) total (fixed and variable) cost of production, inventory, material handling, overhead, and transportation costs. The model outputs included (1) the number and location of distribution centers, (2) the customer-distribution center assignment, (3) the number of echelons (amount of vertical integration), and (4) the product-plant assignment.

Voudouris (1996) developed a mathematical model designed to improve efficiency and responsiveness in a supply chain. The model maximized system flexibility, as measured by the time-based sum of instantaneous differences between the capacities and utilizations of two types of resources: inventory resources and activity resources. Inventory resources are resources directly associated with the amount of inventory held; activity resources, then, are resources that are required to maintain material flow. The models generated as output: (1) a production, shipping, and delivery schedule for each product and (2) target inventory levels for each product.

Camm et al. (1997) developed an integer programming model, based on an uncapacitated facility location formulation, for Procter and Gamble Company. The purposes of the model were to: (1) determine the location of distribution centers (DCs) and (2) assign those selected DCs to customer zones. The objective function of the model minimized the total cost of the DC location selection and the DC-customer assignment, subject to constraints governing DC-customer assignments and the maximum number of DCs allowed.

Gachon and Lariviere (1999) examined how the choice of mechanism impacts retailer actions and supply chain performance. They analyzed turn-and-earn allocation, a method commonly used in the automobile industry. The scheme presented allocations on past sales and thus enabled retailers to influence their future allocations. They found that turn-and-earn induced the retailers to increase theirs sales when demand was low, and the impact on the supply chain depended on how restrictive the capacity was.

2.2.2 Facility Location Problem for Distribution Planning

The distribution/locations family of problems covers formulations, which range in complexity from simple single-product linear deterministic models to multi-product nonlinear stochastic versions. Solution approaches include heuristics, optimizers, simulators, and some innovative hybrid procedures, which embody more than one of these (Aikens, 1985). The purpose of this section is to review some of the significant work, which are related and fundamental to this dissertation. The focus will be on a mathematical model with specific reference to the use of heuristics or optimizers to extract solutions. Distribution/location can be classified according to:

1) Whether the distribution network is capacitated or uncapacitated.
2) The number of warehouse echelons, or levels.
3) The number of commodities (single or multiple).
4) Whether the underlying cost structure is linear or nonlinear.
5) Whether the planning horizon is static or dynamic.
6) Whether the pattern of demand is deterministic or stochastic.
7) The ability to accommodate side constraints.

In 1977, Kaufman et al. proposed an algorithm, which solved a two-level distribution system using branch and bound. The algorithm was used to solve a small and simple uncapacitated multi-echelon facility location problem. Triple subscripting and the double set of binary variables were used in their model. A limitation of their model is the requirement that a warehouse must be located wherever a plant is located.

Warszawski (1973) was one of the pioneers to address multi-product problem. Warszawski examined both a branch and bound procedure and a heuristic for solving multi-product uncapacitated facility location model. However, no computational results were provided for the branch and bound algorithm due to excessive computation time. In 1978, Erlenkotter developed two dual-based algorithms for solving the same problem based on a linear programming dual formation. A simple ascent and adjustment procedure was used to produce optimal dual solutions. The author found that the dual-based algorithm was superior to other existing methods at that time.

Nauss (1978) was one of the first to consider the capacitated location problem. Nauss proposed a branch and bound algorithm along with the use of Lagrangian relaxation, and tighter lower bounds. The relaxation was solved efficiently by decomposition method. This resulted in fewer branches.

The focus on the multi-product capacitated single-echelon facility location problem started in 1974 by Geoffrion and Graves. In the Geoffrion and Graves model, sole-sourcing of customers was mandatory, and transportation costs were determined by the total plant-to-customer route. More amenable model of practical application was developed by Geoffrion, Graves and Lee in 1978. Their work appeared to represent the state-of-the-art for multi-product capacitated location problems. A solution technique based on decomposition was developed, and successfully applied to a real problem.

2.2.3 Differences between the Present Study and the Earlier Studies

The work presented in this study differs in one form or the other from the studies reviewed above in the following aspects:

- The majority of work on supply chain management focused on a push-based supply chain system or make-to-stock principle but in this study the focus is on a pull-based supply chain system or make-to-order/make-to-assembly principle.
- In model formulations, a sole sourcing of customers was mandatory. In this study, the models are capable of formulating problems of a multiple sourcing of customers.
- The majority of work on supply chain management was not flexible and only focused on logistics planning in strategic and/or tactical levels like inventory

positioning and numbers of facilities, sizes, and locations. In this study, the models present all logistics planning decisions including in operational planning level. The models can be effectively used to fill customer order, replenish inventories, and generate production orders throughout the supply chain network.

- The model formulations were either single-product multi-echelon or multi-product single-echelon problem. In this study, the formulations cover multi-product multi-echelon problem.
- Problems of practical size also presented a problem for all the solution methodology. In this study, the heuristic is formulated specifically for large and small size problems.

CHAPTER 3

MODEL DEVELOPMENT FOR SUPPLY CHAIN LOCATION PROBLEM

As stated earlier, the objective of the present study is to develop a procedure for integrating decisions along the supply chain to minimize the total systemwide costs. In this chapter, the framework for the supply chain management system for a single-product and multi-product supply chain management problems at the strategic and tactical planning levels are addressed. At these levels, a company usually focuses on selecting a set of operating facilities within the supply chain. Closing, opening, or expanding production and storage facilities are also the decisions that a company makes at these levels. These types of decision-making have been recognized by researchers and practitioners for decades as "Facility Location Problem". Excellent references and surveys in facility location problem can be found in Aikens (1985) and Drezner (1995). However, a few researchers have focused on multi-product and multi-echelon location problem that link together all related costs within a supply chain (Beamon, 1998). The majority of these previous works mainly focused on either the uncapacitated or capacitated single echelon location problem and did not integrate other decisions in their models. The models generally emphasize either the production or the distribution component but not both components simultaneously. In this chapter, the integrated decision models of the single-product capacitated two-echelon facility location (SCTFL) and the multi-product capacitated two-echelon facility location (MCTFL) problems are presented. Firstly all required data for model development, model characteristic, and the total system-wide costs within a supply chain network are defined.

Next, two mixed integer linear programming problems, SCTFL and MCTFL, are developed and described. Finally, solution procedures and numerical examples of the problems are presented.

3.1 Required Data for Model Development

The data necessary for the development of both the SCTFL and MCTFL models are as followings:

- Average customer order for each product per year.
- A set of candidate warehouses or distribution centers and their maximum storage capacities.
- A set of candidate production plants and their maximum production capacities.
- An average per unit transportation cost per ton-miles between customer locations and distribution centers.
- An average per unit transportation cost per ton-miles between distribution centers and production plants.
- Fixed and variable operation costs when using a particular distribution center or production plant.

3.2 Model Characteristics

The objective of the models for both the single-product and the multi-product two–echelon problems is to determine a set of facility locations, which will minimize total system-wide cost. Two different models representing the single-product and multi-product two-echelon facility location problems are considered. These models are briefly stated below. Details on each model are provided in sections 3.5 and 3.6 respectively.

3.2.1 Assumptions-Applicable to Both Models

The following assumptions are made in developing the two models:

- Any plants can manufacture any products and supply to any distribution centers.
- Any distribution center can supply finish products to any customer locations.
- The location and capacity of each production plant and distribution center are known and fixed.
- Average demand (units per year) for each customer demand point or location is known.
- All distribution centers are resupplied only from the plants. That is, lateral supply among the facilities is not allowed.
- All transportation costs, facility establishment costs, and other related costs are known.

3.2.2 SCTFL Model

A single-product two-echelon facility location (SCTFL) problem consists of a set of plants, distribution centers, and customer locations. In this problem, there is only one product in the supply chain system. The problem exists when a company has a policy to market and manage its product line individually or has only one product line. For example, a computer manufacturing company may divide its product line into printer, computer CPU, and scanner. The company can treat and organize these products individually starting from production and inventory control to product distribution. In this aspect, SCTFL may be used for each product line to determine the best supply chain network configuration, which consists of a set of production plants and stocking point locations and capacities, and primary distribution channel to deliver finish products to the end-customers. This usually happens at the company's strategic and tactical planning levels.

3.2.3 MCTFL Model

Multi-product two-echelon facility location model (MCTFL) represents the supply chain location problem with more than one product line. In this case, there are several product lines, which each production plant manufactures and each distribution center responds to. A company markets and distributes these different products through the same distribution channel or distribution logistics. Each product can be stored at any warehouse or produced at any production facility. Each customer's demand may consists of one or multiple products. Example of this kind of demands exists in most consumer product cases when a retail store such as Kmart, Target, or Walmart orders several goods from a single manufacturer. MCTFL is, then, used to determine the multi-product supply chain configuration network.

3.3 Total Systemwide Costs (TC) in Generalized Supply Chain Network

To model the supply chain problem in this study, first, the total supply chain cost is addressed and broken down into four major categories: 1) production cost, 2) transportation cost, 3) Inventory carrying cost, and 4) warehousing cost. These costs reflect costs of acquiring raw materials, converting raw materials into specified final products, storing the final products, and delivering the final products at desired points. The following is the total systemwide cost function.

$$TC = P_C + T_C + I_C + W_C$$

where, TC = total systemwide cost,

P_C = Production cost,

T_C = Transportation cost,

I_C = Inventory carrying cost,

W_C = Warehousing cost.

3.3.1 Production Cost (P_C)

$$P_C = f_c + v_c$$

Fixed costs **(f_c)**: general administrative expense, taxes and insurance, rent, building and equipment depreciation, utilities, and other costs, that is invariant with the production volume.

Variable costs **(v_c)**: variable costs vary in proportion to quantity of output. These costs are usually for direct material and direct labor cost.

3.3.2 Transportation Cost *(T_C)*

$$T_C = i_c + o_c$$

Or,

$$T_C = i_c + t_{md} + t_{dc}$$

Inbound transportation costs (i_c): the costs of obtaining raw material or costs related to shipping between suppliers and the firm, sometime called "Material procurement costs".

Outbound transportation costs (o_c): costs associated with the shipping charges between the firm and customers. These costs may vary by customer locations and by the firm's channels of distribution. Cost associated with shipping charges between manufacturing sites and distribution centers is denoted by t_{md} and between DCs and customers is denoted by t_{dc}.

3.3.3 Inventory Carrying Cost *(I_C)*

$$I_C = s_c + t_c$$

Storage space costs (s_c): all expenses associated with the quantity or the level of inventory stored. If the space is privately owned or contracted, space costs appear as fixed costs. When the space belongs to a public warehouse, the charges are based on the amount of products moved into and out of the warehouse and the amount of inventory held in storage. Rented or leased warehouse space is normally contracted for a specified period of time. The amount of space rented is based on the maximum storage requirements during the period covered by the contract.

Throughput cost (t_c): this cost is related to selling the product in a given market by moving it in and out of warehouse.

3.3.4 Warehousing Cost *(W_C)*

Warehousing fixed cost (Wc): this cost is primarily fixed and is related to supervision or associated management costs to maintain or operate the warehouses.

3.4 Mathematical Formulation and Notations

To be able to investigate and formulate the mathematical model for the supply chain problem, the total systemwide cost as expressed in the previous section is simplified further as following:

$$TC = C_1 + C_2 + C_3 + C_4 + C_5 + C_6$$

Where,

C_1 = Fixed production cost *(f_c)*

C_2 = Outbound transportation cost from plants to warehouses and variable production cost per unit *($v_c + t_{md}$)*.

C_3 = Outbound per unit transportation cost from warehouses to customers *(t_{dc})*.

C_4 = Warehousing costs and storage space fixed costs *($Wc + s_c$)*.

C_5 = Inventory throughput cost per unit cost *(t_c)*.

C_6 = Material procurement cost per unit cost *(i_c)*.

Now, to model the supply chain network configuration problem, the idea of using separate transportation variables for plant-to-warehouse and warehouse-to-customer shipments, which are less complex, are employed. The approach is different from the well-known, but more complicated, work by Geoffrion and Craves (1974). In their model, triple subscribed variables were used in order to avoid losing the origin of a product once it arrives at a DC or warehouse. This seemed useful when there were no data tracking tools and

Internet technology. With current technology, there is no need to incorporate the origin of a product into the mathematical model. Part tracking information, nowadays, can be captured by bar coding system throughout the supply chain and always stored in a company database.

The use of separate variables not only brings us a new look at the problem, but also seems less complex, more flexible, and essentially easier to approach. It is also easy to incorporate with some supply chain strategies like pull-based supply chain system, order consolidations, postponement, or mixed strategy, which are limited when the triple subscribe variables are used. Beside these issues, by using separate variables, the problem, now, can be decomposed into a set of smaller and easier-to-solve subproblems. The mathematical formulation of the problem throughout this chapter uses the following notation.

p index for commodities,

i index for plants,

j index for possible distribution center (DC) sites, or warehouse locations,

k index for customers or retailers,

P a set of commodities,

I a set of plants,

J a set of warehouses or DC,

K a set of potential customers,

a_{ij}^{p} the unit transportation cost of product p from plant i to warehouse j,

b_i fixed costs for plant i,

c_{jk}^{p} the unit transportation cost of product p from warehouse j to customer/retailer k,

d_j fixed establishment and operating costs of warehouse/DC j,

e_j^p the unit throughput cost of product p at warehouse/DC j,

f_i^p the unit procurement cost of product p at plant i,

A_{ij}^p the total unit logistics cost of product p from plant i to warehouse j,

C_{ij}^p the total unit logistics cost of product p from warehouse j to customer/retailer k,

D_k^p demand of customer/retailer k of product p,

U_j^p maximum inventory capacity of product p at warehouse j,

P_i^p maximum production capacity of product p at plant i,

x_{ij}^p quantity of product p from plant i to warehouse/DC j,

w_{ik}^p quantity of product p from warehouse/DC j to customer/retailer k,

y_i a $0-1$ variable that is1 if a plant is located at site i, and 0 otherwise.

z_j a $0-1$ variable that is 1 if warehouse/DC is located at site j and 0 otherwise.

3.5 Single-product Capacitated Two-echelon Facility Location Problem (SCTFL)

3.5.1 Mixed-Integer Linear Programming

Although the main focus in this study is on the multi-product supply chain problem, we believe that it is better to understand the nature of the easier but similar problem of SCTFL first before moving on to the more complicated MCTFL problem. SCTFL provides not only the fundamental insight required to model the multi-product supply chain problem, but also the heuristic solution to solve similar problems. With the superscript p dropped from the parameters for the single product case, the following is the mixed integer linear programming model for SCTFL.

Problem 1 (P1):

$$\begin{aligned} \textit{Minimize} \quad & \sum_{i=1}^{I}\sum_{j=1}^{J} a_{ij}x_{ij} + \sum_{i=1}^{I} b_i y_i + \sum_{j=1}^{J}\sum_{k=1}^{K} c_{jk}w_{jk} + \sum_{j=1}^{J} d_j z_j \\ & + \sum_{j=1}^{J}\sum_{k=1}^{K} e_j w_{jk} + \sum_{i=1}^{I}\sum_{j=1}^{J} f_i x_{ij} \end{aligned} \tag{3.1}$$

Or

$$\textit{Minimize} \quad \sum_{i=1}^{I}\sum_{j=1}^{J} \left(a_{ij} + f_i\right)x_{ij} + \sum_{i=1}^{I} b_i y_i + \sum_{j=1}^{J}\sum_{k=1}^{K} \left(c_{jk} + e_j\right)w_{jk} + \sum_{j=1}^{J} d_j z_j \tag{3.2}$$

Or

$$\textit{Minimize} \quad \sum_{i=1}^{I}\sum_{j=1}^{J} A_{ij}x_{ij} + \sum_{i=1}^{I} b_i y_i + \sum_{j=1}^{J}\sum_{k=1}^{K} C_{jk}w_{jk} + \sum_{j=1}^{J} d_j z_j \tag{3.3}$$

Subject to

$$\sum_{j=1}^{J} w_{jk} \geq D_k, \qquad \forall\, k \in K, \tag{3.4}$$

$$\sum_{k=1}^{K} w_{jk} \leq U_j z_j, \qquad \forall\, j \in J, \tag{3.5}$$

$$\sum_{i=1}^{I} x_{ij} = \sum_{k=1}^{K} w_{jk}, \qquad \forall\, j \in J, \tag{3.6}$$

$$\sum_{j=1}^{J} x_{ij} \leq P_i y_i, \qquad \forall\, i \in I, \tag{3.7}$$

$$x_{ij} \geq 0, \quad \forall\, i \in I, j \in J, \tag{3.8}$$

$$w_{jk} \geq 0, \quad \forall\, j \in J, k \in K, \tag{3.9}$$

$$y_i, z_j \in \{0, 1\}, \quad \forall\, i \in I, j \in J, \tag{3.10}$$

In this problem, we have a set of potential locations for plants and warehouses with fixed costs and capacities. A product, for a set of customers with known demands, is to be supplied from plants via warehouses. The unit logistics cost for the product supplied from the plants to all customers via warehouses are given. The problem is to find the subset of plants and warehouses that will minimize the total fixed and logistic costs such that the demand for all the customers can be satisfied without violating the capacity constraints of the plants and warehouses. Equation (3.3) is the problem objective function to minimize the total supply chain cost. Constraint (3.4) requires that demand is satisfied and constraints (3.5) and (3.7) prevent upper bound violations of supplies for the warehouses and plants respectively. Constraints (3.6) balance in-flow product and out-flow product at warehouses. Notice that constraints (3.5) and (3.7) can accommodate both upper and lower limits on supply. Constraints (3.5) and (3.7) also ensure that supplies can only be generated from a facility if and only if the facility exists.

3.5.2 Solution Procedure for SCTFL

In this section, a method based on a Lagrangian relaxation is presented. The Lagrangian relaxation scheme has been used successfully in various location and assignment problems (Swain, 1974, Nauss, 1978, Geoffrion and McBride, 1978, Christofides and Beasley, 1983, Sridharan, 1993, Pirkul and Jayaraman, 1996, Park, Lim and Lee, 1998, Holmberg and Hellstrand, 1998). Lagrangian relaxation is an approach used for solving mixed integer and pure integer programming problems. In this section, we present a solution procedure based on Lagrangian relaxation for a Single-product Capacitated Two-echelon Facility Location Problem (SCTFL). We denote our original SCTFL problem by P1 and its relaxed problems by LP (μ), where μ refers to the vector of Lagrangian multipliers used.

According to problem P1, the set of constraints 3.6 is the hard constraint set. Without these constraints SCTFL becomes two separate capacitated single-product single-echelon problem, one for the warehouse location problem and the other for the plant location problem. These two problems are usually called "Capacitated Facility Location Problem (CFL)" and could be solved by many existing methods. By relaxing constraint 3.6 using the Lagrangian multipliers, the relaxation problem becomes as follow:

Lagrangian relaxation of problem 1 (LP(μ)):

$$\text{Minimize} \quad \sum_{i=1}^{I}\sum_{j=1}^{J} A_{ij}x_{ij} + \sum_{i=1}^{I} b_i y_i + \sum_{j=1}^{J}\sum_{k=1}^{K} C_{jk}w_{jk} + \sum_{j=1}^{J} d_j z_j + \sum_{j=1}^{J}\mu_j\left(\sum_{i=1}^{I} x_{ij} - \sum_{k=1}^{K} w_{jk}\right) \qquad (3.11)$$

Or

$$\text{Minimize} \quad \sum_{j=1}^{J}\sum_{i=1}^{I}(A_{ij}+\mu_j)x_{ij} + \sum_{i=1}^{I} b_i y_i + \sum_{j=1}^{J}\sum_{k=1}^{K}(C_{jk}-\mu_j)w_{jk} + \sum_{j=1}^{J} d_j z_j \qquad (3.12)$$

Subject to *Constraints 3.4, 3.5, 3.7, 3.8, 3.9 and 3.10*

Now, assuming a solution Z_{P1} is the optimal solution to P1. It is well-know that $Z_{LP(\mu)} \le Z_{P1}$. However, in general, it is not possible to guarantee finding μ for which $Z_{LP(\mu)} = Z_{P1}$, but this frequently happens for particular problem instances. $Z_{LP(\mu)} \le Z_{P1}$ allows LP to be used in place of P1 to provide lower bounds for the problem. Moreover, good feasible solutions to P1 can be obtained by perturbing nearby feasible solutions to LP(μ). The result of LP(μ) also can be used as an analytic tool for establishing worst-case bounds on the performance of heuristics.

It is obvious that our LP(μ) problems can be further decomposed into the following two subproblems.

Subproblem LP1

$$\text{Minimize} \quad \sum_{j=1}^{J}\sum_{k=1}^{K}(C_{jk}-\mu_j)w_{jk}+\sum_{j=1}^{J}d_j z_j \tag{3.13}$$

Subject to

$$\sum_{j=1}^{J} w_{jk} \geq D_k, \qquad \forall\, k \in K, \tag{3.14}$$

$$\sum_{k=1}^{K} w_{jk} \leq U_j z_j, \qquad \forall\, j \in J \tag{3.15}$$

$$w_{jk} \geq 0, \quad \forall\, j \in J, k \in K, \tag{3.16}$$

$$z_j \in \{0,1\}, \qquad \forall\, j \in J, \tag{3.17}$$

Subproblem LP2

$$\text{Minimize} \quad \sum_{j=1}^{J}\sum_{i=1}^{I}(A_{ij}+\mu_j)x_{ij}+\sum_{i=1}^{I}b_i y_i+\sum_{j=1}^{J}d_j z_j \tag{3.18}$$

Subject to

$$\sum_{i=1}^{I} x_{ij} \leq U_j z_j, \qquad \forall j \in J, \tag{3.19}$$

$$\sum_{j=1}^{J} x_{ij} \leq P_i y_i, \qquad \forall\, i \in I, \tag{3.20}$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J} x_{ij} \geq \sum_{k=1}^{K} D_k, \tag{3.21}$$

$$x_{ij} \geq 0, \quad \forall i \in I, j \in J, \tag{3.22}$$

$$y_i \in \{0,1\}, \qquad \forall i \in I, \tag{3.23}$$

$$z_j \in \{0,1\}, \qquad \forall j \in J, \tag{3.24}$$

In order to solve LP2 separately and feasibly, we add constraints 3.19 and constraints 3.21 into the original set of constraints. Constraints 3.19 are used to prevent upper bound violations of in-flow product into warehouses. Constraint 3.21 is a surrogate constraint, which is added to LP2 to produce tighter lower bounds and also increases the chance of obtaining a feasible solution to P1 during a given Lagrangian relaxation procedure. It makes sure that the in-flow product into warehouse can satisfy total customers' demand.

3.5.2.1 Optimal Solution Properties

It is obvious that the objective value of the relaxation LP(μ) can be found after solving LP1 and LP2 separately. Now let Z_{LP1} be the optimal value of LP1 and Z_{LP2} be the optimal value of LP2. The following is the objective value of LP(μ).

$$Z_{LP(\mu)} = Z_{LP1} + Z_{LP2} - \sum_{j=1}^{J} d_j z'_j \qquad (3.25)$$

Since the fixed costs of using particular warehouses or distribution centers appear on both LP1 and LP2 objective functions, the objective value of LP(μ) in equation 3.25 is the sum of Z_{LP1} and Z_{LP2} less the fixed costs of the particular warehouses (d_j), which are opened or used (i.e., $z'_j = 1$, in both LP1 and LP2).

Now, to guarantee that the value in constraint 3.25 is feasible and optimal, the following properties must hold.

Property 3.1: Let $Z_1(\mu)$ be the set of opened warehouses in LP1, and $Z_2(\mu)$ be the set of opened warehouses in LP2. When $Z_1(\mu) = Z_2(\mu)$, but $\sum_{i=1}^{I} x_{ij} \geq \sum_{k=1}^{K} w_{jk}, \forall j \in J$, the feasible solution of LP(μ) can be obtained by equation 3.25.

Property 3.2: Let μ^* be the set of optimal multipliers. The optimal solution of LP(μ^*) can be found when $Z_1(\mu) = Z_2(\mu)$ and $\sum_{i=1}^{I} x_{ij} = \sum_{k=1}^{K} w_{jk}, \forall j \in J.$, where w_{jk} and x_{ij} are the solutions of LP1(μ^*) and LP2(μ^*) respectively.

However, in general the relaxation LP(μ) might not be able to find μ^* which satisfies Property 3.2. To prevent this situation the following property is used to terminate the Lagrangian Decomposition (LD) heuristic.

Property 3.3: Let μ^* be a set of multipliers. The near optimal solution of LP(μ^*) can be found when $Z_1(\mu) = Z_2(\mu)$ and $\sum_{i=1}^{I} x_{ij} - \sum_{k=1}^{K} w_{jk} \leq \varepsilon, \quad \forall j \in J$, where w_{jk} and x_{ij} are the solutions of LP1(μ^*) and LP2(μ^*) respectively, and ε is a small value.

Alternatively, the LD heuristic also can be terminated using the maximum number of iterations allowed. However, the solution must be feasible or satisfy Property 3.1.

3.5.2.2 Lagrangian Decomposition Heuristic Procedures (LD)

To solve LP(μ) relaxation problem, the following heuristic procedure is used

Step 1: Initiate the multiplier values (μ)

Step 2: Solve LP1(μ) subproblem

- Obtaining $Z_1(\mu)$, w_{jk}, and Z_{LP1}.

Step 3: Solve LP2(μ) subproblem.

- Obtaining $Z_2(\mu)$, x_{ij}, y_i, and Z_{LP2}.

Step 4: Find $Z_{LP(\mu)}$

Step 5: Checking the stopping criteria

- If stopping criteria is satisfied, stop the procedure.

- Otherwise go to Step 6.

Step 6: Update the multiplier values (μ), then go to Step 2.

The following figure 3.1 shows LD heuristic in each iteration.

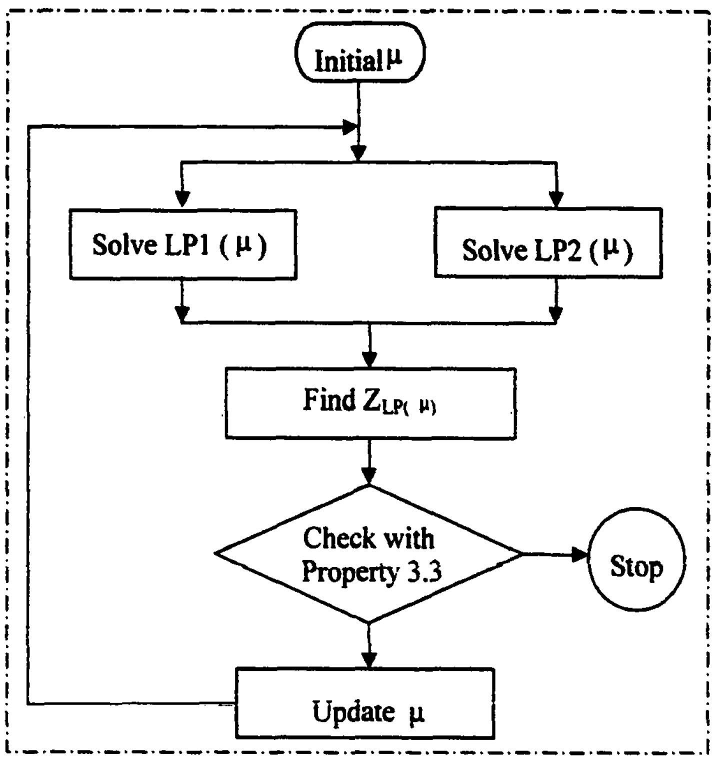


Figure 3.1 LD heuristic in each iteration.

3.5.2.3 Updating Multipliers, μ

There are many existing methods to update the multipliers, μ. However, among the available approaches, the subgradient algorithm seems to work the best for the problem in this study. Very simple and easy to implement without using a linear programming system approach, the multipliers values can be found relatively fast. More details about subgradient and other similar methods can be found in Wolsey (1998), Bertsimas and Orlin (1994), Geoffrion and McBride (1978), Crowder (1976), Camerini, Fratta, and Maffioli (1975), , Geoffrion (1974), Held, Wolfe, and Crowder (1974), Grinold (1970).

Assume Z_{P1} is the objective function value of the feasible solution of the original problem, $Z_{LP(\mu^t)}$ is the objective function value of the solution of the relaxation problem in iteration t,. and, θ_t is a positive scalar between 0 and 2. Then the multipliers, μ^t, in iteration t can be updated as given in Step 6 above using the following steps.

Step 6-1: (Initialization) Let $t \leftarrow 0,\ \mu^t \in (R^m)^+ \ and\ \mu^t > 0$

Step 6-2: $\gamma^t \leftarrow$ is a solution vector of x_{ij}^t and w_{jk}^t after solving LP(μ^t)

Step 6-3: Let $\mu^{t+1} \leftarrow \max\{0, \mu^t + \beta_t \gamma^t\}$, where β_t is a positive scalar called the step size.

β_t can be found by $\beta_t = \dfrac{\theta_t\left(Z_{P1} - Z_{LP(\mu^t)}\right)}{\left\|\gamma^t\right\|^2}$

Step 6-4: $t = t + 1$ and go to Step 2 in the LD Heuristics.

3.6 Multi-product Capacitated Two-echelon Facility Location Problem (MCTFL)

3.6.1 Mixed Integer Linear Programming

MCTFL problem is used to determine facility locations of the whole supply chain when there are several commodities produced at several plants with known production capacities. There is a known demand for each product by each customer or retailer. This demand is satisfied by shipping via regional distribution centers (DC), with each customer/retailer being assigned to at least one DC. There are upper bounds on the allowable total annual throughput of each product at each DC. The possible locations for the DCs are given, but particular sites are to be used depending on the least total systemwide cost. The problem is to determine which DC sites to use for each product, which customers should be served by each DC, which DC should be served by each plant, and what the pattern of transportation flows should be for all products. The following mixed integer programming problem represents MCTFL.

$$\textit{Minimize} \quad \sum_{p=1}^{P}\sum_{i=1}^{I}\sum_{j=1}^{J} A_{ij}^{p} x_{ij}^{p} + \sum_{i=1}^{I} b_i y_i + \sum_{p=1}^{P}\sum_{j=1}^{J}\sum_{k=1}^{K} C_{jk}^{p} w_{jk}^{p} + \sum_{j=1}^{J} d_j z_j \qquad (3.26)$$

Subject to

$$\sum_{j=1}^{J} w_{jk}^{p} \ge D_k^{p}, \qquad \forall\, k \in K, p \in P, \qquad (3.27)$$

$$\sum_{k=1}^{K} w_{jk}^{p} \le U_j^{p} z_j, \qquad \forall\, j \in J, p \in P, \qquad (3.28)$$

$$\sum_{i=1}^{I} x_{ij}^{p} = \sum_{k=1}^{K} w_{jk}^{p}, \qquad \forall\, j \in J, p \in P, \qquad (3.29)$$

$$\sum_{j=1}^{J} x_{ij}^{p} \le P_i^{p} y_i, \qquad \forall\, i \in I, p \in P, \qquad (3.30)$$

$$x_{ij}^{p} \ge 0, \quad \forall\, i \in I, j \in J, p \in P, \qquad (3.31)$$

$$w_{jk}^{p} \ge 0, \quad \forall\, j \in J, k \in K, p \in P, \qquad (3.32)$$

$$y_i, z_j \in \{0, 1\}, \qquad \forall\, i \in I, j \in J, \qquad (3.33)$$

As you see, the problem is to find the subset of plants and warehouses that will minimize the total supply chain costs such that the demand of all the customers can be satisfied without violating the capacity constraints of the plants and warehouses. Equation (3.26) is the problem objective function to minimize the total supply chain costs.

Constraints (3.27) require that each product demand by each customer is satisfied and constraints (3.28) and (3.30) prevent upper bound violations of supply of each product for the selected warehouses and plants respectively. Constraints (3.29) balance the in-flow product and out-flow product at warehouses. Notice that constraint (3.28) uses the upper bound for particular products at the DC or warehouse, so the problem can be decomposed into SCTFL. However, additional procedure needs to be developed to find the optimal solution.

3.6.2 Solution Procedure for MCTFL

It is obvious that MCTFL problem is NP-hard and much more complex than SCTFL problem. Therefore the use of a heuristic approach is appropriate in this case. As you see, MCTFL can be decomposed into P different SCTFL subproblems with some modification of the second and the last terms of the objective constraint (3.26). Based on MCTFL decomposable nature, instead of solving it directly, individual products are treated as SCTFL and then try to improve the solution. The following is the heuristic procedure for MCTFL.

Step 1: Arrange the products in descending order based on the total sales amount.

- Let P' = a set of ranked products.

Step 2: Let p^* be the first product of set P'. Solve SCTFL for product p^*.

- Obtain $Z_{p^*}, w_{jk}^{p^*}, x_{ij}^{p^*}, y_i$ and z_j
- From y_i and z_j, now let $I^* = \{i\}$ and $J^* = \{j\}$, where I^* *and* J^* are sets of plants and DCs respectively that are used

Step 3: Set b_i and $d_j = 0$ for all $i \in I^*$ and $j \in J^*$ in constraint (3.26).

Step 4: Update set $P' = P' - \{p^*\}$.

Step 5: Stop when $P' = \{\varnothing\}$. Otherwise, Go to **Step** 2.

The following figure 3.2 show MCTFL heuristic procedure.

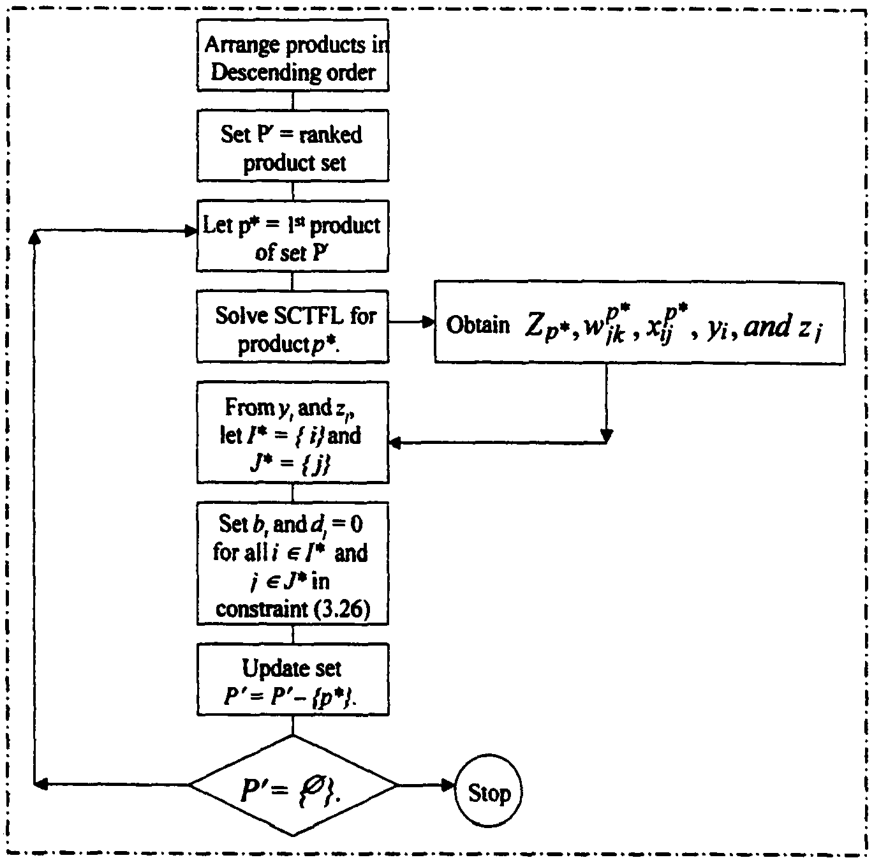


Figure 3.2 MCTFL heuristic procedure.

3.7 Solution Procedures for LP1 and LP2

After decomposing the SCTFL into LP1 and LP2, LP1 and LP2 are solved iteratively using Bender's decomposition concepts. More details about Bender's decomposition can be found in Magnanti (1981), Geoffrion (1972), and Geoffrion and Graves (1971). It is known that Bender's decomposition generates an acceptable result when compared with other large-scale linear integer methods such as Lagrangian relaxation, Dantzig (1960), Dantzig and Wolfe (1961), Geoffrion (1974), Held, Wolfe and Crowder (1974), Christofides and Beasley

(1983), Sridharan (1993), and Branch and Bound, Akinc and Khumawala (1977), Holmberg and Hellstrand (1998), Park, Lim and Lee (1998). However, as mentioned in several literature such as Cornuejols, Sridharan and Thizy (1991), Bender's method has some weaknesses when it deals with complex primal problem, the Bender's master problem. It is quite known that solving the Dual's master problem using Lagrangian multiplier is a lot easier and more efficient than Bender's master problem when using popular solvers or mathematical methods such as Simplex or Karmarkar's interior points, Kamarkar (1984), Vandebei, Meketon, and Freedman (1986), and Todd (1990). Based on this observation, we develop a heuristic to specifically solve Bender's master and subproblem. The developed heuristic generally yields an optimum, or close to optimum for the single echelon location problems. The following are the details of the heuristic procedure.

Bender's decomposition is an iterative procedure that deals with solving two separate problems. One is called Bender's master problem, and the other is called Bender's subproblem. In this study based on LP1, the master and subproblem will be placed in the following generic forms.

$$\underset{z\in[0,1]}{\text{Minimize}} \begin{bmatrix} \underset{w_{jk}\in Z^{+}}{\text{Minimize}} \sum_{j=1}^{J}\sum_{k=1}^{K} C_{jk}w_{jk} + \sum_{j=1}^{J} d_j z_j \\ \text{Subject to} \\ \sum_{j=1}^{J} w_{jk} \geq D_k, \quad \forall k \in K \\ \sum_{k=1}^{K} w_{jk} \leq I_j z_j, \quad \forall j \in J \end{bmatrix} \tag{3.34}$$

$$\text{Subject to} \quad \sum_{k=1}^{k} D_k \leq \sum_{j=1}^{J} I_j z_j \tag{3.35}$$

or its linear programming dual form

$$\underset{z\in[0,1]}{Minimize}\left[\underset{t\in T}{Maximize}\sum_{k=1}^{K} D_k\lambda_k^t + \sum_{j=1}^{J}(d_j - I_j\mu_j^t)z_j\right] \tag{3.36}$$

$$Subject\ to\quad \sum_{k=1}^{k} D_k \le \sum_{j=1}^{J} I_j z_j$$

or

$$\underset{z\in[0,1],\rho}{Minimize}\quad \rho$$

$$Subject\ to\quad \rho \ge \sum_{k=1}^{K} D_k\lambda_k^t + \sum_{j=1}^{J}(d_j - I_j\mu_k^t)z_j,\quad all\ t\in T \tag{3.37}$$

$$\sum_{k=1}^{k} D_k \le \sum_{j=1}^{J} I_j z_j$$

Where T is the index set of all dual feasible basic solutions (λ^t, μ^t) of Bender subproblems and λ and μ correspond to the constraints (3.14) and (3.15) of LP1. The constraints indexed by $t\in T$ are called Benders or primal cuts or Bender subproblems. Benders proposed to solve a relaxation of the original problem by taking only a subset of primal cuts, and to generate cuts when necessary. In each iteration, a primal cut is generated using the dual optimal solution of Bender subproblem and added to Bender master problem. The master is then solved to give a new z and ρ.

For LP2, the master and subproblem will be defined in the following generic forms.

$$\underset{\substack{y\in[0,1],\\ z\in[0,1]}}{\text{Minimize}} \left[\begin{array}{ll} \underset{x_{ij}\in Z^+}{\text{Minimize}} \sum_{i=1}^{I}\sum_{j=1}^{J} A_{ij}x_{ij} + \sum_{i=1}^{I} b_i y_i + \sum_{j=1}^{J} d_j z_j & \\ \\ \text{Subject to} & \\ \quad \sum_{i=1}^{I} x_{ij} \le I_j z_j, & \forall j \in J \\ \quad \sum_{j=1}^{J} x_{ij} \le P_i y_i, & \forall i \in I \\ \quad \sum_{i=1}^{I}\sum_{j=1}^{J} x_{ij} \ge D, & \forall D \text{ is const.} \end{array} \right] \tag{3.38}$$

$$\text{Subject to} \quad D \le \sum_{j=1}^{J} I_j z_j \quad \text{and} \quad D \le \sum_{i=1}^{I} P_i y_i \tag{3.39}$$

or

$$\underset{\substack{y\in[0,1],\\ z\in[0,1],\rho}}{\text{Minimize}} \quad \rho$$

$$\text{Subject to} \quad \rho \ge \sum_{j=1}^{J} (d_j - I_j \mu_j^t) z_j + \sum_{i=1}^{I} (b_i - P_i \mu_i^t) y_i + D\lambda^t, \quad \text{all } t \in T \tag{3.40}$$

$$D \le \sum_{j=1}^{J} I_j z_j \quad \text{and} \quad D \le \sum_{i=1}^{I} P_i y_i$$

Again, T is the index set of all dual feasible basic solutions (λ^t, μ^t) of Bender subproblems, μ correspond to constraints (3.19) and (3.20), and λ correspond to the constraint (3.21). The constraints indexed by $t \in T$ are called Benders or primal cuts or Bender subproblems of LP2.

3.7.1. Solving Bender's Subproblem

The following are examples of Bender's subproblems after fixing the binary variables in LP1 and LP2. For LP1, an instance with three warehouses and four customers is used.

Each of the three warehouses can be used to fill all four customers' orders. The maximum inventory of each warehouse is between 50 to 70 units and the demand of each customer is between 30 to 50 units. The following are the subproblems of this problem.

Bender's Primal subproblem:

$$\begin{aligned}\text{Min}\quad & 2.5w_{11} + 1.9w_{12} + 3w_{13} + 2.7w_{14} + 1.5w_{21} + 2w_{22} + 2.3w_{23} + 2.5w_{24} \\ & + 2.1w_{31} + 3.5w_{32} + 1.1w_{33} + 2.2\,w_{34}\end{aligned}$$

Subject to

$$\begin{array}{llllr}
w_{11} & + w_{21} & + w_{31} & & \geq 30 \\
w_{12} & + w_{22} & + w_{32} & & \geq 40 \\
w_{13} & + w_{23} & + w_{33} & & \geq 35 \\
w_{14} & + w_{24} & + w_{34} & & \geq 50 \\
w_{11} + w_{12} + w_{13} + w_{14} & & & & \leq 50 \\
 & w_{21} + w_{22} + w_{23} + w_{24} & & & \leq 60 \\
 & & w_{31} + w_{32} + w_{33} + w_{34} & & \leq 70
\end{array}$$

All $w_{jk} \geq 0$

Bender's Dual subproblem:

$$\text{Max}\quad 30\lambda_1 + 40\lambda_2 + 35\lambda_3 + 50\lambda_4 - 50\mu_1 - 60\mu_2 - 70\mu_3$$

Subject to

$$\begin{array}{lllllllr}
\lambda_1 & & & & - \mu_1 & & & \leq 2.5 \\
 & \lambda_2 & & & - \mu_1 & & & \leq 1.9 \\
 & & \lambda_3 & & - \mu_1 & & & \leq 3 \\
 & & & \lambda_4 & - \mu_1 & & & \leq 2.7 \\
\lambda_1 & & & & & - \mu_2 & & \leq 1.5 \\
 & \lambda_2 & & & & - \mu_2 & & \leq 2 \\
 & & \lambda_3 & & & - \mu_2 & & \leq 2.3 \\
 & & & \lambda_4 & & - \mu_2 & & \leq 2.5 \\
\lambda_1 & & & & & & - \mu_3 & \leq 2.1 \\
 & \lambda_2 & & & & & - \mu_3 & \leq 3.5 \\
 & & \lambda_3 & & & & - \mu_3 & \leq 1.1 \\
 & & & \lambda_4 & & & - \mu_3 & \leq 2.2
\end{array}$$

All λ_k *and* $\mu_j \geq 0$

For LP2, the example of three plants and four warehouses are used. Each of the three plants can be used to fill demands from all warehouses. The maximum production capacity of each plant is between 50 to 70 units and the demand of each warehouse is between 30 to 50 units. The following are the subproblems of this problem.

<u>Bender's Primal subproblem:</u>

$$\text{Min} \quad 2.5x_{11} + 1.9x_{12} + 3x_{13} + 2.7x_{14} + 1.5x_{21} + 2x_{22} + 2.3x_{23} + 2.5x_{24} + 2.1x_{31} + 3.5x_{32} + 1.1x_{33} + 2.2x_{34}$$

Subject to

$$\begin{aligned}
&x_{11} + x_{21} + x_{31} \le 30\\
&x_{12} + x_{22} + x_{32} \le 40\\
&x_{13} + x_{23} + x_{33} \le 35\\
&x_{14} + x_{24} + x_{34} \le 50\\
&x_{11} + x_{12} + x_{13} + x_{14} \le 50\\
&x_{21} + x_{22} + x_{23} + x_{24} \le 60\\
&x_{31} + x_{32} + x_{33} + x_{34} \le 70\\
&x_{11} + x_{12} + x_{13} + x_{14} + x_{21} + x_{22} + x_{23} + x_{24} + x_{31} + x_{32} + x_{33} + x_{34} \ge 130
\end{aligned}$$

All $x_{jk} \ge 0$

<u>Bender's Dual subproblem:</u>

$$\text{Max} \quad -30\mu_1 - 40\mu_2 - 35\mu_3 - 50\mu_4 - 50\mu_5 - 60\mu_6 - 70\mu_7 + 130\lambda$$

Subject to

$$\begin{aligned}
&-\mu_1 - \mu_5 + \lambda \le 2.5\\
&-\mu_2 - \mu_5 + \lambda \le 1.9\\
&-\mu_3 - \mu_5 + \lambda \le 3\\
&-\mu_4 - \mu_5 + \lambda \le 2.7\\
&-\mu_1 - \mu_6 + \lambda \le 1.5\\
&-\mu_2 - \mu_6 + \lambda \le 2\\
&-\mu_3 - \mu_6 + \lambda \le 2.3\\
&-\mu_4 - \mu_6 + \lambda \le 2.5\\
&-\mu_1 - \mu_7 + \lambda \le 2.1\\
&-\mu_2 - \mu_7 + \lambda \le 3.5\\
&-\mu_3 - \mu_7 + \lambda \le 1.1\\
&-\mu_4 - \mu_7 + \lambda \le 2.2
\end{aligned}$$

All λ_k *and* $\mu_j \ge 0$

To feasibly and effectively solve Bender's subproblems above, we first determine Bender's primal subproblem, which is in the form of a simple transportation problem and easy to solve. Since the problem deals with the large-scale number of integer variables, the application of Vogel's approximation method (VAM), which is known as a near optimal heuristic with less complexity and computational time, is selected to find the primal solution. Next, the affine-scaling method and Cholesky factorization method are utilized to trace out the dual solution. The following are the details of the method.

3.7.1.1. Modified Vogel's Approximation Method for LP1

Step1: Determine the penalty for each row (column) by subtracting the second highest cost element in the row (column) from the highest cost element in the same row (column).

Step2: Determine the row or column with the largest penalty, breaking ties arbitrarily. Allocate as much as possible to the variable with the least cost in the selected row or column. Make adjustment to the supply and demand and then cross out the satisfied row or column. If a row and a column are satisfied simultaneously, just one of them is crossed out and the remaining row (column) is set to zero supply (demand). Any row or column with zero supply or demand should not be used in calculating future penalties (in step 3).

Step3:

a) If exactly one row or one column remains uncrossed out and there is only one row (column) with positive supply, determine the basic variables in the row (column) by the least-cost method (as described in the next section). Stop.

b) If all uncrossed-out rows and columns have (assigned) zero supply and demand, determine the zero basic variables by the least-cost method. Stop.

c) Otherwise, recalculated the penalties for the uncrossed-out rows and columns, then go to step 2. (Notice that the rows and columns with assigned zero supply and demand should not be used in computing these penalties.)

The Least-cost Method

The procedure is as follows. Assign as much as possible to the variable with the smallest unit cost in the entire tableau (Ties are broken arbitrarily.) Cross out the satisfied row or column (If both a column and a row are satisfied simultaneously, only one may be crossed out.) After adjusting the supply and demand for all uncrossed-out rows and columns, repeat the process by assigning as much as possible to the variable with the smallest uncrossed-out unit cost. The procedure is complete when exactly one row or one column remains uncrossed out.

To demonstrate the Vogel method for LP1, an instance with three warehouses and four customers is used. Each of the three warehouses can be used to fill all four customers' orders. The maximum inventory of each warehouse is between 50 to 70 units and the demand of each customer is between 30 to 50 units.

Numerical example for LP1 Bender's subproblem:

Iteration 0	Customer					Supply	Penalty
	1	2	3	4	Dummy		
DCs 1	2.5	1.9 (40)	3.0	2.7	M	50	0.3
2	1.5	2.0	2.3	2.5	M	60	0.2
3	2.1	3.5	1.1	2.2	M	70	1.3
Demand	30	40	35	50			
Penalty	0.4	**1.5**	0.7	0.2			

- The largest penalty is 1.5 at column #2.
- Number of allocated products is 40 units from DC #1 to Customer #2.

Iteration 1	Customer					Supply	Penalty
	1	2	3	4	Dummy		
DCs 1	2.5	1.9 (40)	3.0	2.7	M	10	0.3
2	1.5	2.0	2.3	2.5	M	60	0.2
3	2.1	3.5	1.1 (35)	2.2	M	70	0.1
Demand	30	40	35	50			
Penalty	0.4		**0.7**	0.2			

- Number of allocated products is 35 units from DC #3 to Customer #3.

Iteration 2	Customer					Supply	Penalty
	1	2	3	4	Dummy		
DCs 1	2.5	1.9 40	3.0	2.7	M	10	0.2
2	1.5 30	2.0	2.3	2.5	M	60	1.0
3	2.1	3.5	1.1 35	2.2	M	35	0.1
Demand	30	40	35	50			
Penalty	0.4			0.2			

- Column #3 is crossed out and updated supply of DC #3 is 35 units.
- The largest penalty is 1.0 at row #2.
- Number of allocated products is 30 units from DC #2 to Customer #1.

Iteration 3	Customer					Supply	Penalty
	1	2	3	4	Dummy		
DCs 1	2.5	1.9 40	3.0	2.7	M	10	
2	1.5 30	2.0	2.3	2.5 15	M	30	
3	2.1	3.5	1.1 35	2.2 35	M	35	
Demand	30	40	35	50			
Penalty							

- Column #1 is crossed out and updated supply of DC #2 is 30 units.
- Since there is only one remaining column, the least-cost method is used.

- Number of allocated product is 35 and 15 units from DC #3 to Customer #4 and from DC #2 to Customer #4, respectively.

Iteration Final	**Customer**					Supply	Penalty
	1	**2**	**3**	**4**	**Dummy**		
DCs 1	2.5	1.9 40	3.0	2.7	M	10	
2	1.5 30	2.0	2.3	2.5 15	M	15	
3	2.1	3.5	1.1 35	2.2 35	M	0	
Demand	30	40	35	50			
Penalty							

- Updated supply of DC #2 is 15 units and DC #3 is zero.

3.7.1.2. Modified Vogel's Approximation Method for LP2

Step 1: Set D = total needed product (total demands at DCs level).

Step 2: Determine a penalty for each row (column) by subtracting the second highest cost element in the row (column) from the highest cost element in the same row (column)

Step 3: Determine the row or column with the largest penalty, breaking ties arbitrarily. Allocate N product units to the variable with the least cost in the selected row or column, where N = minimize (demand, supply, D). Make adjustment to the supply and demand and then cross out the satisfied row or column. If a row and a column are satisfied simultaneously, just one of them is crossed out and the remaining row (column) is set to zero supply (demand). Any row or column with zero supply or demand should not be used in calculating future penalties (in step 4).

Step 4:

a) If exactly one row or one column remains uncrossed out and there is only one row (column) with positive supply (demand), determine the basic variables in the row (column) by the least-cost method to allocate the remaining D. Then update D value. Stop.

b) If all uncrossed-out rows and column have (assigned) zero supply and demand, determine the zero basic variables by the least-cost method to allocate the remaining D. Stop.

c) Otherwise, recalculate the penalties for the uncrossed-out rows and columns and update D value, then go to step 3. (Notice that the rows and columns with assigned zero supply and demand should not be used in computing these penalties.)

To demonstrate the Modified Vogel's Approximation method for LP2, an example of three plants and four warehouses are used. Each of the three plants can be used to fill demands from all warehouses. The maximum production capacity of each plant is between 50 to 70 units and the demand of each warehouse is between 30 to 50 units.

Numerical example for LP2 Bender's subproblem:

Iteration 0	Warehouse 1	2	3	4	Supply	Penalty
Plant 1	2.5	1.9 40	3.0	2.7	50	0.3
2	1.5	2.0	2.3	2.5	60	0.2
3	2.1	3.5	1.1	2.2	70	1.3
Demand	30	40	35	25		
Penalty	0.4	1.5	0.7	0.2		

- Total needed product = 130 units
- Number of allocated products = min{40, 50, 130} = 40 units

Iteration 1	Warehouse 1	2	3	4	Supply	Penalty
Plant 1	2.5	1.9 40	3.0	2.7	10	0.3
2	1.5	2.0	2.3	2.5	60	0.2
3	2.1	3.5	1.1 35	2.2	70	0.1
Demand	30	40	35	25		
Penalty	0.4		0.7	0.2		

- Total needed product = {130 – 40} = 90 units.
- Number of allocated products = min{35, 70, 90} = 35 units

Iteration 2	Warehouse 1	2	3	4	Supply	Penalty
Plant 1	2.5	1.9 40	3.0	2.7	10	0.2
2	1.5 30	2.0	2.3	2.5	60	1.0
3	2.1	3.5	1.1 35	2.2	35	0.1
Demand	30	40	35	25		
Penalty	0.4			0.2		

- Total needed products = {90 – 35} = 55 units.

- Number of allocated products = min{30, 60, 55} = 30 units.

Iteration 2	Warehouse 1	2	3	4	Supply	Penalty
Plant 1	2.5	1.9 40	3.0	2.7	10	
2	1.5 30	2.0	2.3	2.5	30	
3	2.1	3.5	1.1 35	2.2 25	35	
Demand	30	40	35	25		
Penalty						

- Total needed products = {55 – 30} = 25 units.

- Number of allocated product = min{50, 35, 25} = 25 units.

3.7.1.3. Finding Dual Subproblem Solution from the Primal Subproblem Solution

In order to quickly estimate the dual solution from the primal outcome, the knowledge of the affine-scaling method and the Numeric Cholesky factorization are utilized. The following standard optimization problems are used to demonstrate the method.

$$\begin{aligned}
&\text{Primal}: \textit{Minimize} \quad c^T w \\
&\qquad\quad \textit{Subject to} \quad Aw = b \quad w \geq 0 \\
&\text{Dual}: \quad \textit{Maximum} \quad b^T \lambda \\
&\qquad\quad \textit{Subject to} \quad A^T \lambda \leq c \quad \lambda \textit{ is free}
\end{aligned}$$

<u>**How to apply the affine-scaling method**</u>

To find the dual solution, the original problem is scaled using an affine transformation. The following are the scaled problem and its scaling relationship.

$$\begin{aligned}
&\text{Primal} \quad : \textit{Minimize} \quad c_1^T w_1 \\
&\qquad\qquad \textit{Subject to} \quad A_1 w_1 = b \quad w_1 \geq 0
\end{aligned}$$

Where

$$w_1 = D^{-1} x \qquad A_1 = AD \qquad c_1 = Dc,$$

and

$$w_1 = \begin{bmatrix} 1 \\ 1 \\ \vdots \\ \vdots \\ 1 \end{bmatrix}, \quad D = \begin{bmatrix} w_1 & & & & \\ & w_2 & & & \\ & & \cdots & & \\ & & & \cdots & \\ & & & & w_n \end{bmatrix}$$

According to the affine-scaling method, the dual solution can be estimated when there is an available primal solution. For more information about the affine-scaling method, the reader is referred to Arbel (1993). The equation below is used to estimate the solution vector for the dual problem when the original problem is in the scaling form using affine transformation.

$$\lambda = (AD^2A^T)^{-1} AD^2c \quad or \quad (AD^2A^T)\,\lambda = AD^2c \tag{3.41}$$

How to apply Chelosky Factorization

As you see, to find the inverse matrix, $(AD^2A^T)^{-1}$, is an expensive operation and in most cases is not needed for obtaining the solution to the system of equation. To avoid this costly operation, Chelosky factorization method is applied. Chelosky factorization method is a solution approach for general linear system of equations, which has a symmetry. It is also known as one of the best methods for a computer based solution. Since, the matrix, (AD^2A^T) in equation (3.41) is symmetric, the Cholesky factorization of (AD^2A^T) can be written as

$$AD^2A^T = LL^T \tag{3.42}$$

The m x m lower triangular matrix L is referred to as the Cholesky factor. To derive the Cholesky factor, the product form of (AD^2A^T) can be written out in an explicit manner as following.

$$AD^2A^T = \begin{bmatrix} a_{11} & a_{12} & \cdots & \cdots & a_{1m} \\ a_{21} & a_{22} & \cdots & \cdots & a_{2m} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ a_{m1} & a_{m2} & \cdots & \cdots & a_{mm} \end{bmatrix} = LL^T = \begin{bmatrix} l_{11} & 0 & \cdots & \cdots & 0 \\ l_{21} & l_{22} & \cdots & \cdots & 0 \\ & \cdots & \cdots & \cdots & \cdots \\ & \cdots & \cdots & \cdots & \cdots \\ l_{m1} & l_{m2} & \cdots & \cdots & l_{mm} \end{bmatrix} \begin{bmatrix} l_{11} & l_{21} & \cdots & \cdots & l_{m1} \\ 0 & l_{22} & \cdots & \cdots & l_{m2} \\ \cdots & \cdots & \cdots & \cdots & \\ \cdots & \cdots & \cdots & \cdots & \\ 0 & 0 & \cdots & 0 & l_{mm} \end{bmatrix}$$

To come up with the factor in this study, the column-wise Cholesky factorization algorithm Arbel (1993) is performed. The row-wise Cholesky factorization algorithm can be found in Martin (1999). The column-wise algorithm is described below.

$$\begin{aligned}
&For\ q = 1, 2, ..., m : (column\ indexes)\\
&\quad l_{qq} = \sqrt{a_{qq} - \sum_{j=1}^{q-1} l_{qj}^2} \quad (diagonal\ element)\\
&\quad For\ i = q+1, ..., m : (row\ indixes)\\
&\qquad l_{iq} = \frac{a_{iq} - \sum_{p=1}^{q-1} l_{ip} l_{qp}}{l_{qq}} \qquad (elements\ below\ the\ diagonal)\\
&\quad End\\
&End
\end{aligned}$$

Now, suppose a matrix (AD^2A^T) is factored through a Cholesky factorization scheme, the solution to the symmetric system of equations, now, can be easily obtained using a forward and backward solve cycles. Based on the equation (3.41) and (3.42), the original problem now becomes

$$LL^T\lambda = AD^2c \tag{3.43}$$

Next, by defining $v = L^T\lambda$ equation (3.43) is rewritten as

$$Lv = AD^2c \tag{3.44}$$

and because L is a lower triangular matrix, finding this system solution is easily accomplished. Suppose the vector $b = AD^2c$. Writing (3.44) explicitly becomes

$$\begin{bmatrix} l_{11} & 0 & \dots & \dots & 0 \\ l_{21} & l_{22} & \dots & \dots & 0 \\ & \dots & \dots & \dots & \dots \\ & \dots & \dots & \dots & \dots \\ l_{m1} & l_{m2} & \dots & \dots & l_{mm} \end{bmatrix} \begin{bmatrix} v_1 \\ v_2 \\ \dots \\ \dots \\ v_m \end{bmatrix} = \begin{bmatrix} b_1 \\ b_2 \\ \dots \\ \dots \\ b_m \end{bmatrix} \tag{3.45}$$

Finding the system solution shown above can be accomplished in a forward manner by starting to solve for v_1 from the first equation, followed by solving for v_2 from the second equation, and so on. This process is called a forward solve cycle. Once the solution for v is available, the process of solving the vector λ can begin using the following system.

$$L^T\lambda = v \tag{3.46}$$

Since L^T is an upper triangular matrix, the solution process, first, starts by solving for λ_m. and going backward toward obtaining the solution for λ_1. This solution process is known as a backward solve cycle.

The affine-scaling and Chelosky factorization methods are demonstrated next through the same numerical example used earlier in demonstrating the VAM method in section 3.7.1.1.

Affine-scaling & Chelosky factorization numerical Example

$$\begin{aligned} Min \quad & 2.5w_{11} + 1.9w_{12} + 3w_{13} + 2.7w_{14} + 1.5w_{21} + 2w_{22} + 2.3w_{23} + 2.5w_{24} \\ & + 2.1w_{31} + 3.5w_{32} + 1.1w_{33} + 2.2\, w_{34} \end{aligned}$$

Subject to

$$\begin{aligned}
w_{11} + w_{21} + w_{31} &\geq 30 \\
w_{12} + w_{22} + w_{32} &\geq 40 \\
w_{13} + w_{23} + w_{33} &\geq 35 \\
w_{14} + w_{24} + w_{34} &\geq 50 \\
w_{11} + w_{12} + w_{13} + w_{14} &\leq 50 \\
w_{21} + w_{22} + w_{23} + w_{24} &\leq 60 \\
w_{31} + w_{32} + w_{33} + w_{34} &\leq 70
\end{aligned}$$

All $w_{jk} \geq 0$

Suppose the primal solution of the problem is $w_{12} = 40$, $w_{21} = 30$, $w_{24} = 15$, $w_{33} = 35$, and $w_{34} = 35$. The following vectors can be formed.

$$c = \begin{bmatrix} 2.5 \\ 1.9 \\ 3.0 \\ 2.7 \\ 1.5 \\ 2.0 \\ 2.3 \\ 2.5 \\ 2.1 \\ 3.5 \\ 1.1 \\ 2.2 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}, \qquad W = \begin{bmatrix} 0 \\ 40 \\ 0 \\ 0 \\ 30 \\ 0 \\ 0 \\ 15 \\ 0 \\ 0 \\ 35 \\ 35 \\ 0 \\ 0 \\ 0 \\ 0 \\ 10 \\ 15 \\ 0 \end{bmatrix}$$

$$A = \begin{bmatrix} 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & -1 & 0 & 0 & 0 \\ -1 & -1 & -1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & -1 & -1 & -1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & -1 & -1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

Step 1: Given the primal solution from VAM, the scaling matrix, D, AD^2A^T and the vector AD^2c are formed. These are as given below.

$$D=\begin{bmatrix}
0 \\
& 40 \\
& & 0 \\
& & & 0 \\
& & & & 30 \\
& & & & & 0 \\
& & & & & & 0 \\
& & & & & & & 15 \\
& & & & & & & & 0 \\
& & & & & & & & & 0 \\
& & & & & & & & & & 35 \\
& & & & & & & & & & & 35 \\
& & & & & & & & & & & & 0 \\
& & & & & & & & & & & & & 0 \\
& & & & & & & & & & & & & & 0 \\
& & & & & & & & & & & & & & & 0 \\
& & & & & & & & & & & & & & & & 10 \\
& & & & & & & & & & & & & & & & & 15 \\
& & & & & & & & & & & & & & & & & & 0
\end{bmatrix}$$

$$AD^2A^T=\begin{bmatrix}
900 & 0 & 0 & 0 & 0 & -900 & 0 \\
0 & 1600 & 0 & 0 & -1600 & 0 & 0 \\
0 & 0 & 1225 & 0 & 0 & 0 & -1225 \\
0 & 0 & 0 & 1450 & 0 & -225 & -1225 \\
0 & -1600 & 0 & 0 & 1700 & 0 & 0 \\
-900 & 0 & 0 & -225 & 0 & 1350 & 0 \\
0 & 0 & -1225 & -1225 & 0 & 0 & 2450
\end{bmatrix},\quad AD^2c=\begin{bmatrix}
1350.0 \\ 3040.0 \\ 1347.5 \\ 3257.5 \\ -3040.0 \\ -1912.5 \\ -4042.5
\end{bmatrix}$$

Step 2: Solve for the estimate of the dual vector, λ, from equation (3.41). Begin by applying Cholesky factorization algorithm to find the lower triangular matrix, Cholesky factor from the matrix AD^2A^T. The result of this method is given below.

$$L = \begin{bmatrix} 30.00 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 40.00 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 35.00 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 38.08 & 0 & 0 & 0 \\ 0 & -40.00 & 0 & 10.00 & 0 & 0 & 0 \\ -30.00 & 0 & 0 & -5.91 & 0 & 20.37 & 0 \\ 0 & 0 & -35.00 & -32.17 & 0 & -9.33 & 10.15 \end{bmatrix}$$

Step 3: Applying a forward solve cycle, namely, solving for v from equation (3.44)

$$\begin{bmatrix} 30.00 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 40.00 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 35.00 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 38.08 & 0 & 0 & 0 \\ 0 & -40.00 & 0 & 10.00 & 0 & 0 & 0 \\ -30.00 & 0 & 0 & -5.91 & 0 & 20.37 & 0 \\ 0 & 0 & -35.00 & -32.17 & 0 & -9.33 & 10.15 \end{bmatrix} \begin{bmatrix} v_1 \\ v_2 \\ v_3 \\ v_4 \\ v_5 \\ v_6 \\ v_7 \end{bmatrix} = \begin{bmatrix} 1350.0 \\ 3040.0 \\ 1347.5 \\ 3257.5 \\ -3040.0 \\ -1912.5 \\ -4042.5 \end{bmatrix}$$

The result of this process is given below.

$$v = \begin{bmatrix} 45.00 \\ 76.00 \\ 38.50 \\ 85.55 \\ 0.00 \\ -2.80 \\ 3.05 \end{bmatrix}$$

Step 4: Apply a backward solve cycle, namely, solve for λ from the equation (3.44).

$$\begin{bmatrix} 30.00 & 0 & 0 & 0 & 0 & -30.00 & 0 \\ 0 & 40.00 & 0 & 0 & -40.00 & 0 & 0 \\ 0 & 0 & 35.00 & 0 & 0 & 0 & -35.00 \\ 0 & 0 & 0 & 38.08 & 10.00 & -5.91 & -32.17 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 20.37 & -9.33 \\ 0 & 0 & 0 & 0 & 0 & 0 & 10.15 \end{bmatrix} \begin{bmatrix} \lambda_1 \\ \lambda_2 \\ \lambda_3 \\ \lambda_4 \\ \mu_1 \\ \mu_2 \\ \mu_3 \end{bmatrix} = \begin{bmatrix} 45.00 \\ 76.00 \\ 38.50 \\ 85.55 \\ 0.00 \\ -2.80 \\ 3.05 \end{bmatrix}$$

The result of this process, which is the dual subproblem solution, is given below.

$$\lambda = \begin{bmatrix} 1.50 \\ 1.90 \\ 1.40 \\ 2.50 \\ 0.00 \\ 0.00 \\ 0.30 \end{bmatrix}$$

3.7.2. Solving Bender's Master Optimal Problem, BMO

The following is an example of Bender's Master Problem in a supply chain system that includes the single echelon system in both LP1 and LP2 decomposition problem.

$$\textit{Min} \quad \rho \tag{3.47}$$

$$\textit{Subject to} \quad \rho \geq 21 + 2Y_1 - 4Y_2 - 7Y_3$$

$$\rho \geq 12 + 0Y_1 + 3Y_2 + 3Y_3$$

$$\rho \geq 15 - 2Y_1 + 0Y_2 + 3Y_3$$

$$10Y_1 + 20Y_2 + 30Y_3 \geq 30 \tag{3.48}$$

$$Y_1, Y_2, Y_3 \in \{0,1\}$$

As mentioned in the earlier chapters, the objective of this study is to develop a heuristic to deal with large-scale problem with an acceptable computational time. Therefore, the problem is solved using an iterative heuristic procedure. BMO is established based on a penalty concept similar to Vogel's approximation and Dynamic Programming methods. In all experimental problems, BMO method could yield an optimum with a short computational time. Details of the method are explained below.

BMO's heuristic procedures

First, let I be the set of binary variables in the master problem, and let J be the set of constraints that have the variable (Y), except constraint (3.48). Then, let I_0 be the set of binary variables, Y_i, that has a zero value, and let I_1 be the set of binary variables, Y_i, that has the value of one, ($I = I_0 \cup I_1$). Now, let Z^B be the best objective value so far, Z^k be the objective value at iteration k, and S_j^k be the constraint value when considering only constraint j in iteration k (the rest of the constraints are temporarily ignored). Also, let S_{ij} be another constraint value when considering only constraint j while letting Y_i in I_1 equal to zero, and a_{ij} be the coefficient of Y_i variables in constraint j. Finally, let b_{ij} be the coefficient of Y_i variable and D be the constant value on the right hand side of constraint (3.48). The detailed steps of the procedure and an example of BMO table are as follows:

BMO heuristic procedures:

Step 0: Set $I_0 = \{\emptyset\}$, $I_1 = \{I\}$, and $k = 0$,

Step 1: Evaluate S_j^k value for $\forall j \in J$ by letting $Y_i = 1$ for $i \in I_1$, and $Yi = 0$ for $I \in I_0$.

Step 2: Evaluate Z_{max} value where $Z_{max} = \underset{\forall j \in J}{Max}(S_j^k)$, and let $Z^k = Z_{max}$

and $Z^B = Z^k$.

Step 3: Increase k value by one.

Step 4: Evaluate S_{ij} value where $S_{ij} = \{S_j^{k-1} - a_{ij}\}$, for $i \in I_1$, and $j \in J$.

Step 5: Find S_i value where $S_i = \text{Max}\ \{S_{ij}: j \in J\}$, for $i \in I_1$.

Step 6: Evaluate Z^k value where $Z^k = \text{Min}\ \{S_i: i \in I_1\}$, and let $i^* = i$ which has the minimum value of S_i.

Step 7:

a) If $Z^k \leq Z^B$ and $\sum_{i=1}^{I'} b_i Y_i \geq D, \forall I' = \{I_1 - i^*\}$, let $Z^B = Z^k$ and move i^* from I_1 to I_0, then go to Step 8.

b) If $Z^k \leq Z^B$ but $\sum_{i=1}^{I'} b_i Y_i \leq D, \forall I' = \{I_1 - i^*\}$, remove S_{i^*} from the consideration, then go back to Step 6.

c) Otherwise, Stop.

Step 8: a) If $|I_1| = 1$, Stop.

b) Set S_j^k value where $S_j^k = S_{i^*j}$ for $j \in J$, and i^* is the result from Step 6. Then go to Step 3.

Figure 3.3 shows an example of BMO table used to store all variables generated by the heuristic in each iteration. The example table represents a problem involving three 0-1 variables and three constraints.

a_{11} S_{11}	a_{12} S_{12}	a_{13} S_{13}	S_1^k
a_{21} S_{21}	a_{22} S_{22}	a_{23} S_{23}	S_2^k
a_{31} S_{31}	a_{32} S_{32}	a_{33} S_{33}	S_3^k
S_1	S_2	S_3	Z^k

Figure 3.3 Shows all variables in BMO table.

BMO numerical example, referred to (3.47):

Min ρ

Subject to $\rho \geq 21 + 2Y_1 - 4Y_2 - 7Y_3$

$\rho \geq 12 + 0Y_1 + 3Y_2 + 3Y_3$

$\rho \geq 15 - 2Y_1 + 0Y_2 + 3Y_3$

$10Y_1 + 20Y_2 + 30Y_3 \geq 30$

$Y_1, Y_2, Y_3 \in \{0,1\}$

k = 0

$I_0 = \{\varnothing\}$, and $I_1 = \{1, 2, 3\}$. D = 30

$Z^B = 18$

2 S_{11}	-4 S_{12}	-7 S_{13}	12
0 S_{21}	3 S_{22}	3 S_{23}	18
-2 S_{31}	0 S_{32}	3 S_{33}	16
			18

k = 1

2 10	-4 16	-7 19	16
0 18	3 15	3 15	15
-2 18	0 16	3 19	16
18	16	19	16

Based on step 6: i* = 2

Based on step 7(c): $16 \le Z^B$ and $\{10 + 30\} \ge D$, new $Z^B = 16$.

$$I_0 = \{2\}, \text{ and } I_1 = \{1, 3\}$$

Based on step 8(b): $S_1^1 = 16$, $S_2^1 = 15$, and $S_3^1 = 16$.

k = 2

2 14	-4 16	-7 23	
0 15	3 15	3 12	
-2 18	0 16	3 13	
18	16	23	18

Based on step 6: i* = 1

Based on step 7(c): $18 \ge Z^B$, Stop.

The optimal objective value is 16, and the optimal solution is $\{Y_1 = 1, Y_2 = 0$, and $Y_3 = 1\}$. The heuristic stops in the second iteration since $Z^2 > Z^B$.

3.8. Chapter Summary

In this chapter, the framework for the supply chain management system for a single-product and multi-product supply chain management problems at the strategic and tactical planning levels were addressed. The problems are focused on selecting a set of operating facilities within the supply chain. At first, all required data for model development, model characteristic, and the total systemwide costs within a supply chain network were defined. Next, two mixed integer linear programming problems, SCTFL and MCTFL, were developed and described.

To solve these two problems, heuristic methods based on decomposition technique were introduced. MCTFL problem was decomposed to SCTFL problem. SCTFL problem was decomposed to LP1 and LP2. To feasibly and effectively solve LP1 and LP2, Bender's decomposition concepts were used. A set of new heuristic methods to specifically solve Bender's master and sub problems was developed. The application of Vogel's Approximation Method (VAM), the affine-scaling method, and Cholesky factorization were utilized or modified to trace out the solution of Bender's subproblem.

Finally, a new method called BMO was introduced to find Bender's master solution. The method was established based on a penalty concept similar to VAM and Dynamic Programming methods. In all experimental problems, BMO method could yield an optimum solution within a short computational time.

CHAPTER 4

MODEL DEVELOPMENT FOR A PULL-BASED SUPPLY CHAIN SYSTEM

4.1. General Introduction

As mention in the previous chapters, in order to minimize a company's systemwide costs, all decisions along the supply chain need to be considered together at the same time. In this chapter SCTFL method from chapter 3 is applied to the pull-based supply chain system at a company operational level. Two heuristic procedures, one for a single-product and the other for multi-product aspects are then developed to determine the optimal customers' order filling, production plan, and inventory replenishment decisions. The studied supply chain system consists of two echelons, customers vs. distribution centers and distribution centers vs. manufacturing plants.

4.2. Generic Supply Chain Model

In this section, two generic supply chain models are first created. One deals with two-echelon case, which consists of plants, DCs, and customer locations. The other deals with a single echelon, which consists of either plants and DCs, or DCs and customers. The difference between these two models and their uses depends on how a company fulfills its customers' orders and the way the company replenishes its inventory. The first model represents the situation when there are not enough available stocks at the DC level to respond to customers' orders. In this case the company needs to retrieve the ordered products from the plant level via DCs, to fulfill its customers' orders. Another situation is when the company needs to replenish inventory when inventory drops below the safety stock level after filling customers' orders at the DC level. The second model represents a single echelon case between plants vs. DCs, and DCs vs. customers. This ideal single echelon model is used to represent a situation when there are enough on-hand inventories to fill customers' orders without retrieving products from the plant level. In this situation, products are allocated from DCs to each customer location, referred to here as Model 2.1. Another single echelon case deals with the situation when each DC needs to replenish its inventory from plants, referred to here as Model 2.2.

Model 1: Generic model for two echelon distribution system consisting of plants, DCs, and customer sites.

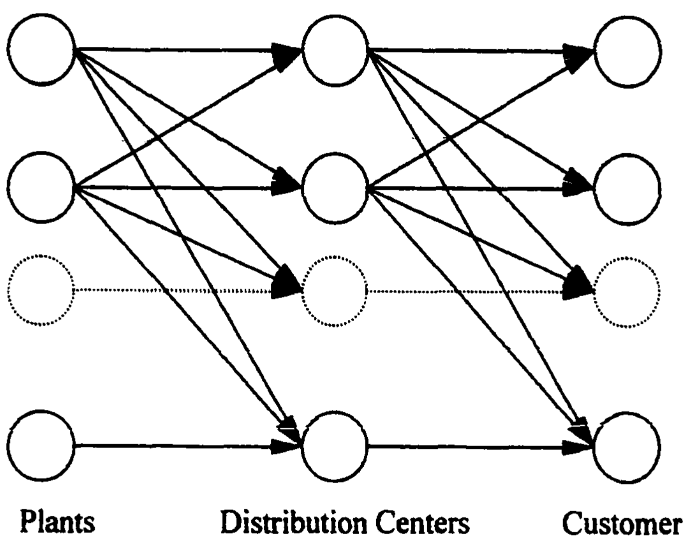


Figure 4.1 Two echelon distribution network

Model 2: Generic model for one echelon distribution system consisting.

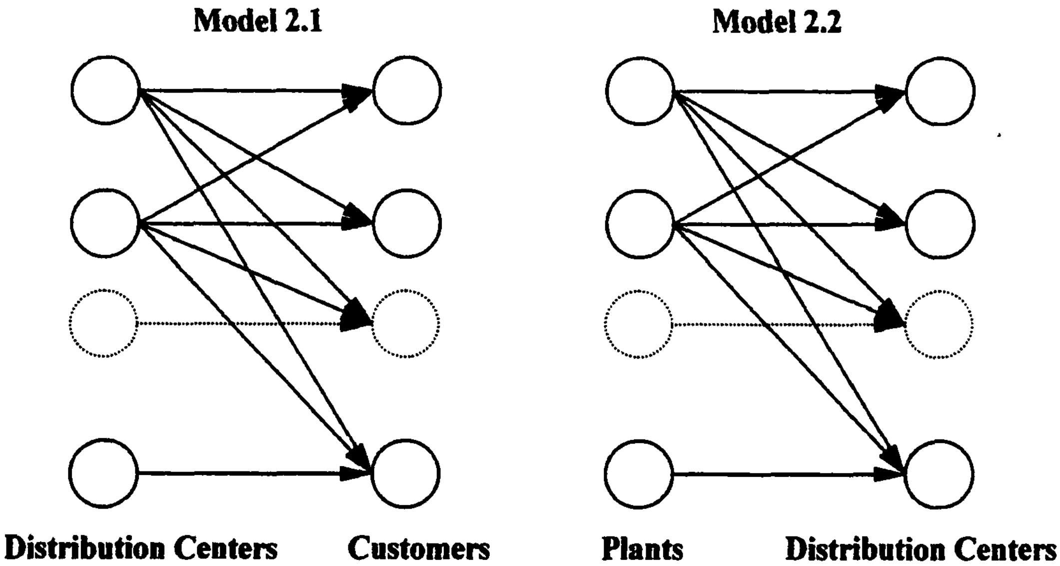


Figure 4.2 One echelon distribution network.

Model Assumptions:

1) The model deals with only one product at a time.
2) The model mainly focuses on integrating advanced production planning, inventory control, and distribution planning.
3) All plants can supply goods to all DCs.
4) All DCs can supply goods to all customers.
5) No plants are allowed to directly supply goods to customers.
6) The model focuses on Make to Order business.
7) Actual demands come from Sales and Marketing.
8) No transshipment between distribution centers.
9) No transshipment between plants.
10) All transshipments have a short lead-time.

The mathematical formulation of the problem throughout this chapter uses the following notation.

p index for commodities,

i index for plants,

j index for possible distribution center (DC) sites, or warehouse locations,

k index for customers or retailers,

P a set of commodities,

I a set of plants,

J a set of warehouses or DC,

K a set of customers,

a_{ij}^{p} the unit transportation cost of product p from plant i to warehouse j,

b_{i}^{p} fixed setup costs for product p at plant i,

c_{jk}^{p} the unit transportation cost of product p from warehouse j to customer/retailer k,

d_{j} fixed processing costs at warehouse j/DC j

e_{j}^{p} the unit throughput/processing cost of product p at warehouse/DC j,

f_{i}^{p} the unit procurement cost of product p at plant i,

D_{k}^{p} demand of customer/retailer k of product p,

U_{j}^{p} maximum inventory capacity of commudity p at warehouse j,

P_{i}^{p} maximum production capacity of product p at plant i,

x_{ij}^p quantity of product p from plant i to warehouse/DC j,

w_{jk}^p quantity of product p from warehouse/DC j to customer/retailer k,

y_i^p a 0 – 1 variable that becomes 1 if product p is produced at plant i, and 0 otherwise.

z_j^p a 0 – 1 variable that will be 1 if warehouse/DC j is used to fill customer orders, and 0 otherwise.

4.3. General Solution Concept and Techniques

In pull-base supply chain system, execution is initiated in response to customer order. At the time of execution of the system, demand is known with certainty. This means that production and distribution of products must accurately reflect the real demand. All processes in the customer order cycle, replenishment cycle, and manufacturing cycle are triggered by the arrival of a customer order. In this study, order fulfillment takes places from finish-product inventory if they are available. But in a situation where not enough stock may be on hand to fill customer requests, all processes in the replenishment and manufacturing cycle are started. Both replenishment and manufacturing cycles are thus parts of the customer order fulfillment process in the customer order cycle.

To effectively solve this complex problem, we first study all product movements within the system. There are four possible product movements or cases that may happen when sales orders are received from end customers within a specific time window. With the superscript p dropped from the parameters for the single product case, the following is the mixed integer linear programming model for all four cases.

Case 1: To fill customer orders, product shipments from plants via DCs need to be performed, using Model 1.

This deals with the case where there is not enough inventory at the right or optimal DC locations to directly satisfy customer orders.

$$\text{Minimize} \quad \sum_{i=1}^{I}\sum_{j=1}^{J}(a_{ij}+f_i)x_{ij}+\sum_{i=1}^{I}b_i y_i+\sum_{j=1}^{J}\sum_{k=1}^{K}(c_{jk}+e_j)w_{jk}+\sum_{j=1}^{J}d_j z_j \qquad (4.1)$$

Subject to

$$\sum_{j=1}^{J} w_{jk} \geq D_k, \qquad \forall\, k \in K, \qquad (4.2)$$

$$\sum_{k=1}^{K} w_{jk} \leq U_j z_j, \qquad \forall\, j \in J, \qquad (4.3)$$

$$\sum_{i=1}^{I} x_{ij} = \sum_{k=1}^{K} w_{jk}, \qquad \forall\, j \in J, \qquad (4.4)$$

$$\sum_{j=1}^{J} x_{ij} \leq P_i y_i, \qquad \forall\, i \in I, \qquad (4.5)$$

$$x_{ij} \geq 0, \quad \forall\, i \in I, j \in J, \qquad (4.6)$$

$$w_{jk} \geq 0, \quad \forall\, j \in J, k \in K, \qquad (4.7)$$

$$y_i, z_j \in \{0,1\}, \quad \forall\, i \in I, j \in J, \qquad (4.8)$$

In this case, a company has a set of supply plants and distribution centers with fixed costs and capacities. The finished goods, for a set of customers with known demands, are to be supplied from plants via DCs/warehouses. The total transportation cost incurred include the cost of the products supplied from plants to DCs and from DCs to customers, along with fixed production and fixed DCs operation costs. The problem is to determine the policies on distribution, inventory control, and production planning both at the plants and DCs levels that will minimize the total supply chain costs while satisfying all customer demands without violating the production and storage capacity constraints of the plants and DCs. Equation (4.1) is the problem objective function, to minimize the total supply chain cost. Constraint (4.2) requires that demand be satisfied and constraints (4.3) and (4.4) prevent upper bound violations of supplies for the warehouses and plants respectively. Constraints (4.5) balances in-flow products and out-flow products at warehouses. Constraints (4.3) and (4.5) also ensure that supplies can only be generated from a facility if and only if the facility exists.

Case 2: Shipments from DCs to customers, using Model 2.1

In this case, it is assumed there are maximum stock levels at the time to fill the customers' orders at the DC level. The total maximum inventory is also greater than total customers' demands and all customers' order can be filled without generating production orders at the manufacturing plants.

$$\text{Minimize} \quad \sum_{j=1}^{J} \sum_{k=1}^{K} (c_{jk} + e_j) w_{jk} + \sum_{j=1}^{J} d_j z_j \tag{4.9}$$

Subject to

$$\sum_{j=1}^{J} w_{jk} \geq D_k, \qquad \forall\, k \in K, \tag{4.10}$$

$$\sum_{k=1}^{K} w_{jk} \leq I_j z_j, \qquad \forall\, j \in J \tag{4.11}$$

$$w_{jk} \geq 0, \quad \forall\, j \in J, k \in K, \tag{4.12}$$

$$z_j \in \{0, 1\}, \qquad \forall\, j \in J, \tag{4.13}$$

(Where I_j is the maximum product inventory at DC j.)

Case 3: Shipment from DCs to customers with consideration of on hand inventory level, at DCs using Model 2.1

In this case, there is enough on-hand inventories at the DC level to fill customer orders, again, without generating any production orders at the plant level. The on-hand stocks of all DCs are greater than all customers' orders.

$$\text{Minimize} \quad \sum_{j=1}^{J}\sum_{k=1}^{K}(c_{jk}+e_j)w_{jk}+\sum_{j=1}^{J}d_jz_j \qquad (4.14)$$

Subject to

$$\sum_{j=1}^{J}w_{jk}\geq D_k, \qquad \forall\, k\in K, \qquad (4.15)$$

$$\sum_{k=1}^{K}w_{jk}\leq (H_j-R_j)z_j, \qquad \forall\, j\in J \qquad (4.16)$$

$$w_{jk}\geq 0, \quad \forall\, j\in J, k\in K, \qquad (4.17)$$

$$z_j\in\{0,1\}, \qquad \forall\, j\in J, \qquad (4.18)$$

Remark:

$$\sum_{j=1}^{J}(H_j-R_j)\geq\sum_{k=1}^{K}D_k \qquad (4.19)$$

Where H_j = On hand inventory of DC_j

R_j = Reorder point of DC_j

Case 4: Shipment from plants to DCs with consideration of demands at DCs level, using Model 2.2

$$\text{Minimize} \quad \sum_{i=1}^{I}\sum_{j=1}^{J}(a_{ij}+f_i)x_{ij}+\sum_{i=1}^{I}b_iy_i \qquad (4.20)$$

Subject to

$$\sum_{i=1}^{I} x_{ij} \geq D_j, \quad \forall j, \tag{4.21}$$

$$\sum_{j=1}^{J} x_{ij} \leq P_i y_i, \quad \forall i, \tag{4.22}$$

$$x_{ij} \geq 0, \quad \forall i \in I, j \in J, \tag{4.23}$$

$$y_i \in \{0,1\} \quad \forall i \in I, \tag{4.24}$$

Replenishment takes place when demands at the DC level, D_j are known. D_j can be found by the following conditions:

$$\begin{gathered} E_j = H_j - R_j - \sum_{k=1}^{K} w_{jk} \\ D_j = \begin{cases} 0 & when \quad E_j \geq 1 \\ I_j - E_j & otherwise \end{cases} \end{gathered} \tag{4.26}$$

Where E_j = decision variable

H_j = On hand inventory of DC_j

R_j = Reorder point of DC_j

I_j = Maximum allowed inventory at DC_j

In this case, there are not enough on-hand inventories at the DC level, and production orders have to be generated at the plant level to satisfy customers' demand. It is worth to note that this case will be used only when the demands at DC level are known. According to the pull-based concept, the demand at DC level will be tied to the safety stock level or reorder point of each DC. Therefore, the model will not only fulfill the customers' orders but will at the same time replenish inventories at the DC level at the same time as well.

4.4. Solution Methodology for a Pull-based Supply Chain in a Single-product Problem (PSCSP)

It is obvious that execution in the customer order cycle, replenishment cycle, and manufacturing cycle depends on on-hand inventories and reorder points at the DC levels. If there are enough on-hand inventories and inventory replenishments are not required, only the solutions of case 3 may be necessary. However, if there are not enough on-hand inventories or inventory replenishments are required, the solutions of case 1 may be needed. Base on the mathematical models in previous section, it is intuitive that solving a single-echelon allocation problem like case 3 is much easier than a two-echelon allocation problem in case 1.

To effectively solve the problem, heuristic procedures are designed to investigate the outcome of a single-echelon problem first prior to dealing with a two-echelon problem. If the outcome of a single-echelon problem requires inventory replenishment or logistics cost is too expensive, the outcome of a two-echelon problem may be needed. The following is a heuristic procedure to determine the optimal customer order filling, inventory replenishment, and production decisions when a pull-based supply chain is applied for a single-product case.

Notation:

Let S^i = Optimal objective value for case i, i = 1, 2, 3, and 4.

S^* = Overall optimal objective value.

W_i, Z_i = A set of solutions for case i, i = 1, 2, and 3.

Xi, Yi = A set of solutions for case i, i = 1 and 4.

W^*, Z^*, X^*, Y^* = Overall optimal solution.

C1 = Total distribution cost from DCs to customers.

C2 = Total distribution cost from Plants to DCs.

A Heuristic Procedure for PSCSP

Step 1: Solve case 2 for S^2 and (W_2, Z_2)

Step 2: Solve case 3 for S^3 and (W_3, Z_3)

Step 3: Compare S^2 and S^3. If $S^3 = S^2$, set $S^* = S^3$, X^* and $Y^* = 0$, $W^* = W_3$, and $Z^* = Z_3$, then stop. Otherwise go to next step.

Step 4: Solve case 1 for S^1 and $(X_1, Y_1, W_1$, and $Z_1)$.

Step 5: Compare S^1 and S^3. If $S^3 \leq S^1$, set $S^* = S^3$, X^* and $Y^* = 0$, $W^* = W_3$, and $Z^* = Z_3$, then stop. Otherwise go to next step.

Step 6: Let $W_4 = W_1$ and $Z_4 = Z_1$, and Find C1.

Step 7: Find all demands at Plant – DCs level, D_j, by using condition (4.26). Then solve case 4 for C2 and (X_4, Y_4).

Step 8: Find S^4, which is the total operation cost of C1 and C2. Then set $S^* = S^4$, $X^* = X_4$ and $Y^* = Y_4$, $W^* = W_1$, and $Z^* = Z_1$.

The following figure 4.3 shows a pull-based heuristic procedure.

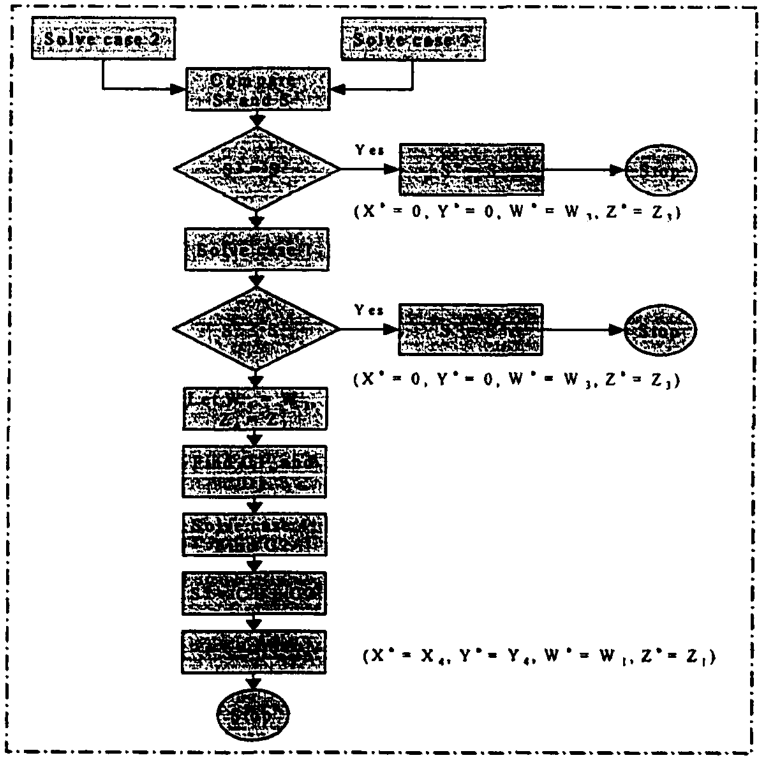


Figure 4.3 A pull-based heuristic procedure

4.5. Solution Methodology for a Pull-based Supply Chain in Multi-product Problem (PSCMP)

A pull-based supply chain in multi-product problem is used in making decisions involving multiple products. It is used in finding the best decision in fulfilling customers' orders, replenishing inventory, and establishing production orders and plans for the whole supply chain for all products. Like the single-product problem, there are known customers' demands for each product during each decision instance. There are also known throughput capacity or upper bounds for each product at each DC and plant. The possible candidate locations for the DCs and plants are also given. The problem is to determine which facility sites should be used in order to minimize the total supply chain costs when considering all product movements at the same time. A key element of this aggregate model is to determine the candidates sites for the plants and DCs that should be selected. The following mixed integer programming problem represents the pull-based supply chain in multi-product. Remark: this model represents a day-by-day decision or operational decision level.

$$\text{Minimize} \quad \sum_{p=1}^{P}\sum_{i=1}^{I}\sum_{j=1}^{J}(a_{ij}^{p}+f_{i}^{p})x_{ij}^{p}+\sum_{p=1}^{P}\sum_{i=1}^{I}b_{i}^{p}y_{i}^{p}+\sum_{p=1}^{P}\sum_{j=1}^{J}\sum_{k=1}^{K}(c_{jk}^{p}+e_{j}^{p})w_{jk}^{p} + \sum_{j=1}^{J}\sum_{k=1}^{K}d_{j}z_{j} \tag{4.25}$$

Subject to

$$\sum_{j=1}^{J} w_{jk}^{p} \geq D_{k}^{p}, \qquad \forall\, k \in K, p \in P, \tag{4.26}$$

$$\sum_{k=1}^{K} w_{jk}^{p} \leq U_{j}^{p} z_{j}, \qquad \forall\, j \in J, p \in P, \tag{4.27}$$

$$\sum_{i=1}^{I} x_{ij}^{p} = \sum_{k=1}^{K} w_{jk}^{p}, \qquad \forall\, j \in J, p \in P, \tag{4.28}$$

$$\sum_{j=1}^{J} x_{ij}^{p} \leq P_{i}^{p} y_{i}^{p}, \qquad \forall\, i \in I, p \in P, \tag{4.29}$$

$$x_{ij}^{p} \geq 0, \quad \forall\, i \in I, j \in J, p \in P, \tag{4.30}$$

$$w_{jk}^{p} \geq 0, \quad \forall\, j \in J, k \in K, p \in P, \tag{4.31}$$

$$y_{i}^{p}, z_{j} \in \{0,1\}, \quad \forall\, i \in I, j \in J, p \in P, \tag{4.32}$$

It is clear that the model is very much the same as MCTFL in section 3.6.1 of chapter 3, except that the fixed costs at plant level, b_i^p, is now defined based on each product. The fixed cost mainly deals with the manufacturing cost of each product at different plants. Notices that the establishment cost at plant level, which is defined in MCTFL, is not part of b_i^p, since the problem, now, deals with a decision in operational level or day-by-day decision level. Normally, the establishment cost at plant level happens in the strategic and tactical level. This assumption is also true for the warehouse fixed cost, d_j. The warehouse fixed cost in operational level normally deals with the operating costs related to hiring/paying shipping and handling personnel and fee. This also is true at the plant level where hiring and paying for general labor takes place. So, this cost is not product specific like b_i^p at plant level but one time charge whenever a particular warehouse is used to fill customer orders in a particular time period. For example, suppose the time period is weekly. This means that the warehouse fixed cost will represent a weekly fixed operating cost. This cost may include other costs such as material handling and shipping equipment costs if applicable.

As you see, PSCMP can be decomposed as PSCSP into P different problems with some modification to the last term of the objective function (4.25). Furthermore, in some situations, the transportation costs associated with the first and the third terms of the same objective function may also need to be modified if it happens that an incentive transportation rate is used to ship in large quantities. This kind of rate is widely used, especially in Less-Than-Truckload (LTL), and Truckload (TL) motor carrier business. It is used to encourage shippers to increase shipment size and allow carriers to better utilize the capacity of their equipment. With the consideration of incentive rates, the unit transportation cost a_{ij}^p in the first term and c_{jk}^p in the third term must be modified. Based on the nature of the problem and the complication of the transportation rate structure, instead of solving the problem directly, the problem is attacked as a PSCSP problem, solved one product at a time. Then in each iteration, all associated costs, previously mentioned, are updated. Figure 4.4 shows a heuristic for a pull-based supply chain of multi-product case.

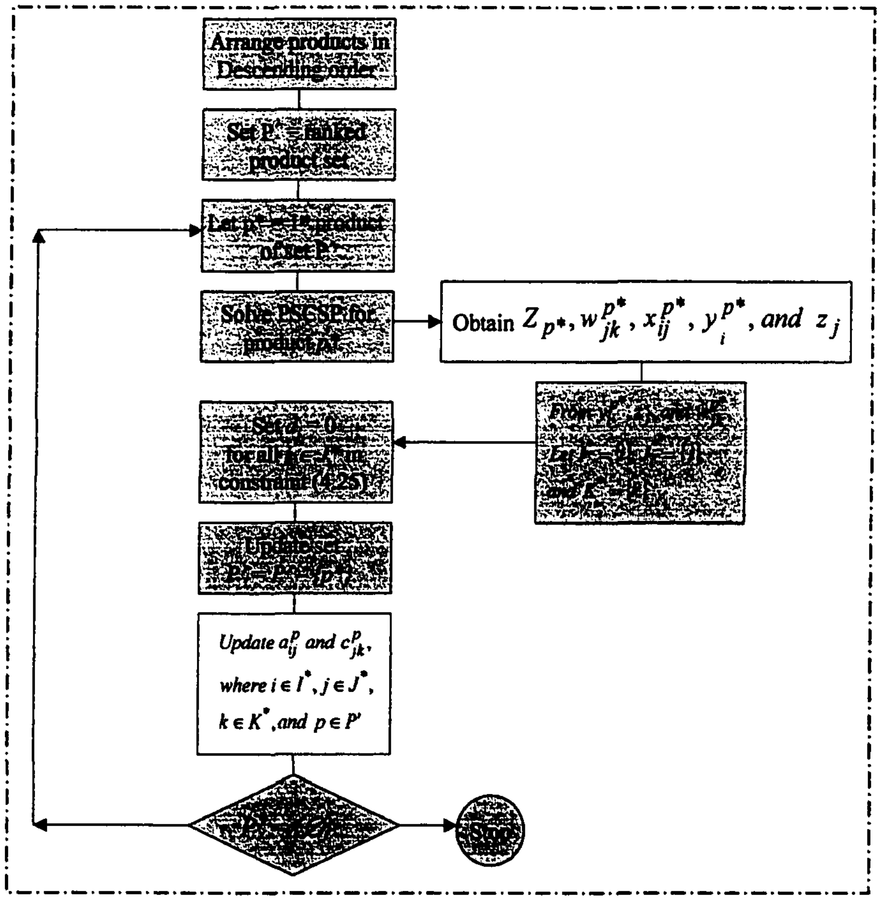


Figure 4.4 A heuristic for a pull-based supply chain of multi-product case

The following is the heuristic procedure for PSCMP.

Step 1: Arrange the products in descending order based on the total sales amount.

- Let P' = a set of ranked products

Step 2: Let p^* be the first product of set P'. Solve PSCSP.

- Obtain $Z_{p*}, w_{jk}^{p*}, x_{ij}^{p*}, y_{i}^{p*}$ and z_j

- From y_i^{p*}, z_j, and w_{jk}^{p*}, now let $I^* = \{i\}$, $J^* = \{j\}$, and $K^* = \{k\}$, where I^*, J^*, and K^* are sets of used plants, used DCs, and customer/retailer locations, respectively.

Step 3: Set $d_j = 0$ for all $j \in J^*$ in equation (4.25).

Step 4: Update set $P' = P' - \{p^*\}$.

Step 5: Update a_{ij}^p and c_{jk}^p, where $i \in I^*, j \in J^*, k \in K^*, and\, p \in P'$.

- Subtract Δ from a_{ij}^p or c_{jk}^p where Δ is an incentive transportation rate. Remark: this step can be omitted if an incentive transportation rate is not applicable)

Step 6: Stop when $P' = \{\emptyset\}$. Otherwise, Go to **Step** 2.

4.6 Chapter Summary

In this chapter, the framework for the pull-base supply chain management system for a single-product and multi-product supply chain management problems at the day-by-day or operational level was addressed. The problems are focused on determining the optimal customers' order filling, production plan, and inventory replenishment decisions. At first, two generic supply chain networks were defined. One represented a single echelon case and another represented a two-echelon case. Next, all possible product movements within the pull-based supply chain were described based on these two generic networks. Four mixed integer linear programming problems were used to represent all four possible product movements in a single product supply chain management problem.

To solve the single product problem, PSCSP, a heuristic method based on the idea of investigating the outcome of a single-echelon problem first prior to dealing with a two-echelon problem was introduced. The developed decomposition methods in the previous chapter were then used to find solutions. To solve the pull-based supply chain in a multi-product problem, PSCMP, the problem was first decomposed as PSCSP into P different problems. Then PSCSP was solved one problem or product at a time. In each iteration, all associated costs were updated and the heuristic process continued until the last product was considered.

CHAPTER 5

COMPUTATIONAL PERFORMANCE

5.1 Numerical Examples

In an effort to evaluate the performance of the solution methodology developed in Chapters 3 and 4, the following tasks were undertaken:

- Tested the supply chain network configuration with a single product, SCTFL, (on 10 example problems with a weekly average demand of 500 customers within the supply chain network of ten warehouses and four manufacturing plants) and compared the results with other two heuristic algorithms (Shortest Distance and Lowest Transportation methods).

- Tested the supply chain network configuration with multiple product, MCTFL, (on 10 example problems with a weekly average demand of 15 products from 500 customers within the supply chain network of ten warehouses and four manufacturing plants) and compared the results with other three heuristic algorithms (Shortest Distance, Lowest Transportation Cost, and Single Warehouse Preference methods).

- Tested the Pull-base Supply Chain method for a single product problem, PSCSP, (on 10 example problems with a weekly demand of a single product from 500 customers within the supply chain network of ten warehouses and four manufacturing plants. Each example problem consists of 13 weeks (one quarter) of sales. In each week, there are 30 to 100 sales order items and compared the results with other two heuristic algorithms (Shortest Distance and Lowest Transportation Cost methods).

- Tested the Pull-base Supply Chain method for the multi product case, PSCMP, (on 10 example problems with a weekly demand of 15 products from 500 customers within the supply chain network of ten warehouses and four manufacturing plants. Each example problem consists of 13 weeks (one quarter) of sales. In each week, there are 550 to 1000 item-sales orders and compared the results with other three heuristic algorithm (Shortest Distance, Lowest Transportation Cost, and Single Warehouse Preference methods).

All testing data were randomly generated. Ten sets of problems were generated for SCTFL and MCTFL. Each set was comprised of an average weekly demand of 500 orders, which can be filled from ten different warehouses and four different plants. There is a single product in SCTFL and a total of 15 products in MCTFL To compare the PSCSP and PSCMP methods, another set of problems was generated that primarily involves week by week operations,. Each set of problems consists of 13 weeks (one quarter) of sales. In each quarter, there are about 700 sales order items in PSCSP and about 10000 sales order items in PSCMP). In each week, there are about 30 to 80 sales order items in PSCSP and about 750 sales order items in PSCMP. Again all customers' orders are filled from a network that involve ten different warehouses and four different plants. An example of customers' orders is appended in Appendix A. Example results solved using heuristic procedures in this study are appended in Appendix B, and C.

5.2 Comparison of Results for SCTFL versus Other Two Heuristic Methods

Recall in chapter 3 that the SCTFL model developed was based on a single product strategy. In an effort to assess the effectiveness of the SCTFL method with the two heuristics, 10 sets of randomly generated problems with 500 customers were solved. In each set of problem, there is a single product involved. The reason for this comparison was to assess the difference in the solution quality and performance between the methods. This type of comparison is helpful in identifying the trade-offs between the methods. These problems were solved via the program developed in this study, on a Pentium III 800 personal computer. Table 5.1 to 5.3 shows the results of each method. Each column contain the following information:

- Column 1 shows the problem number.
- Column 2 shows the total number of customers in the problem.
- Column 3 shows the total number of sales order items.
- Column 4 shows the total costs at warehouses and customers level, denoted as Cost 1.
- Column 5 shows the total costs at plants and warehouses level, denoted as Cost 2.
- Column 6 shows the total supply chain costs (Cost 1 plus Cost 2).
- Column 7 shows the number of actual warehouses used out of some possible number of warehouses.

- Column 8 shows the number of actual plants used out of some possible number of plants.
- Column 9 shows the total CPU time to arrive at the solution.

The main thing to note in looking at these results is that SCTFL heuristic method will always generate equal or less total number of used warehouses and plants than the other two methods. SCTFL heuristic method will also generate less total costs at both warehouses vs. customers and plants vs. warehouses level.

Table 5.1 Results of SCTFL problems using the shortest distance method

Problem #	# of Customers	# of SO items	Cost 1	Cost 2	Total Costs	# of WHs	# of Plants	CPU Time (minutes)
1	500	500	209,249	814,084	1,023,333	10	4	5.24
2	500	500	224,974	553,514	778,488	10	4	4.09
3	500	500	281,095	919,264	1,200,359	10	4	4.25
4	500	500	246,179	556,653	802,832	10	4	4.36
5	500	500	470,619	2,387,762	2,858,381	10	4	4.23
6	500	500	156,852	546,109	702,961	10	4	4.07
7	500	500	159,350	604,636	763,986	10	4	4.10
8	500	500	372,973	933,279	1,306,252	10	4	4.25
9	500	500	239,200	570,328	809,528	10	4	5.29
10	500	500	269,179	512,698	781,877	10	4	4.21

Table 5.2 Results of SCTFL problems using the lowest transportation cost method

Problem #	# of Customers	# of SO items	Cost 1	Cost 2	Total Costs	# of WHs	# of Plants	CPU Time (minutes)
1	500	500	195,869	829,411	1,025,280	10	4	5.30
2	500	500	211,681	558,196	769,877	10	4	4.07
3	500	500	261,497	974,511	1,236,008	10	4	4.26
4	500	500	230,223	571,047	801,270	10	4	4.37
5	500	500	436,439	2,392,518	2,828,957	10	4	4.20
6	500	500	148,119	552,121	700,240	10	4	4.06
7	500	500	151,881	611,941	763,822	10	4	4.10
8	500	500	349,045	962,532	1,311,577	10	4	4.24
9	500	500	225,037	586,340	811,377	10	4	5.29
10	500	500	253,481	518,630	772,111	10	4	4.21

Table 5.3 Results of SCTFL problems using SCTFL heuristic method

Problem #	# of Customers	# of SO items	Cost 1	Cost 2	Total Costs	# of WHs	# of Plants	CPU time (minutes)
1	500	500	192,591	734,502	927,093	6	3	63.23
2	500	500	215,793	330,805	546,598	4	3	45.05
3	500	500	287,026	652,137	939,163	6	4	61.21
4	500	500	232,911	433,971	666,882	6	3	75.35
5	500	500	466,027	1,626,888	2,092,915	5	2	55.15
6	500	500	131,377	448,323	579,700	4	3	49.09
7	500	500	140,337	342,568	482,905	6	3	49.19
8	500	500	381,618	653,749	1,035,367	7	4	88.58
9	500	500	226,673	469,266	695,939	7	4	44.04
10	500	500	244,714	405,885	650,599	6	4	45.50

Table 5.4 shows a comparison of the results for SCTFL problems that were solved using the shortest distance, the lowest transportation cost, and the heuristic methods. The performance measurement employed in this comparison was quality of solutions. As indicated by this table, SCTFL heuristic solutions for all 10 tests outperformed that of the shortest distance and the lowest transportation cost methods. The shortest distance in the worst case came within 58.21% and in the best case came within 10.38% of the solution obtained by SCTFL heuristic. The lowest transportation cost in the worst case came within 58.17% and in the best case came within 10.59% of solution obtained by SCTFL heuristic. However, in all cases the shortest distance and the lowest transportation cost methods outperformed SCTFL heuristic in the CPU time it took to find the best solution. SCTFL heuristic in the worst case took 88.58 minutes and in the best case took 44.04 minutes to find the solution. While comparing between the shortest distance and the lowest transportation cost methods, there was not much difference in both the quality of solutions and the CPU time. Note that the percentage difference in solution equals ((Method II – Method I) ÷ Method I) * 100%.

Table 5.4 Comparison of SCTFL problems using shortest distance, lowest transportation cost, and the SCTFL heuristic methods

Problem #	Shortest Distance	Lowest Trans. Cost	SCTFL Heuristic	% Diff. in Sol. Shortest vs. Lowest	% Diff in Sol. Shortest vs. SCTFL	% Diff in Sol. Lowest vs. SCTFL
1	1,023,333	1,025,280	927,093	0.10	10.38	10.59
2	778,488	769,877	546,598	-1.10	42.42	40.85
3	1,200,359	1,236,008	939,163	2.88	27.81	31.61
4	802,832	801,270	666,882	-0.19	20.39	20.15
5	2,858,381	2,828,957	2,092,915	-1.04	36.57	35.17
6	702,961	700,240	579,700	-0.39	21.26	20.79
7	763,986	763,822	482,905	-0.02	58.21	58.17
8	1,306,252	1,311,577	1,035,367	0.41	26.16	26.68
9	809,528	811,377	695,939	0.23	16.32	16.59
10	781,877	772,111	650,599	-1.26	20.18	18.68

Overall, the SCTFL heuristic outperformed the two other heuristics in the quality of solutions obtained while the two other heuristics dominated the SCTFL heuristic in the amount of CPU time required to solve the problems. From a practical standpoint, given the low cost availability of computers in our time, it is obvious that the cost savings obtained from using the SCTFL heuristics will more than pay for the cost of the computer time required in solving the problems. Therefore, in spite of the poor performance of the SCTFL heuristic in CPU time requirement relative to the other heuristics, it is still more beneficial to adopt the SCTFL heuristic under real life applications than to adopt any of the other two solution approaches presented in this study

5.3 Comparison of Results for MCTFL Versus Other Three Heuristic Methods

In an effort to see how well the MCTFL performed against other three heuristic methods, 10 sets of problems with 500 customers were solved. In each set of randomly generated problems, there were 15 products involved. The average weekly sales order items were randomly generated and ranged from one to fifteen products for each customer. In each problem, on average there were 3,750 sales items ordered. The results of the 10 problems that were solved using the shortest distance, the lowest transportation cost, the single warehouse preference, and MCTFL heuristic methods are given in Tables 5.5, 5.6, 5.7, and 5.8. These tables contain the following information:

- Column 1 shows the problem number.
- Column 2 shows the total number of customers in the problem.
- Column 3 shows the total number of sales items ordered.
- Column 4 shows the total cost at the warehouse and customer interface level, denoted as Cost 1.
- Column 5 shows the total costs at the plant and warehouse interface level, denoted as Cost 2.
- Column 6 shows the total supply chain costs (Cost 1 plus Cost 2).
- Column 7 shows the number of actual warehouses used out of some possible number of warehouses.
- Column 8 shows the number of actual plants used out of some possible number of plants.
- Column 9 shows the total CPU time to arrive at the solution.

Table 5.5 Results of MCTFL problems using the shortest distance method

Problem #	# of Customers	# of SO items	Cost 1	Cost 2	Total Costs	# of WHs	# of Plants	CPU time (minutes)
1	500	3610	1,780,740	6,286,225	8,066,965	10	4	40.17
2	500	3802	1,987,264	6,889,144	8,876,408	10	4	42.47
3	500	3789	1,920,961	6,726,362	8,647,323	10	4	42.27
4	500	3794	2,011,373	7,021,158	9,032,531	10	4	41.30
5	500	3765	1,850,833	6,449,736	8,300,569	10	4	42.33
6	500	3713	1,850,833	6,576,087	8,426,920	10	4	41.50
7	500	3704	1,827,389	6,497,490	8,324,879	10	4	41.52
8	500	3744	1,834,156	6,533,978	8,368,134	10	4	41.57
9	500	3692	1,772,311	6,329,314	8,101,625	10	4	40.43
10	500	3701	1,831,924	6,477,249	8,309,173	10	4	41.05

The key thing to note is that in all of the problems, Cost 2, which is the total cost at plants vs. warehouses level, is always greater than Cost 1, which is the total cost at warehouses vs. customers level. This is because Cost 2 was not only included transportation costs as in Cost 1 but also included the product standard costs as defined in section 3.3 and 3.4 in Chapter 3.

Table 5.6 Results of MCTFL problems using the lowest transportation cost method

Problem #	# of Customers	# of SO items	Cost 1	Cost 2	Total Costs	# of WHs	# of Plants	CPU time (minutes)
1	500	3610	1,522,454	6,026,685	7,549,139	10	4	39.12
2	500	3802	1,630,966	6,451,210	8,082,176	10	4	40.27
3	500	3789	1,630,448	6,463,799	8,094,247	10	4	39.27
4	500	3794	1,665,393	6,570,241	8,235,634	10	4	39.22
5	500	3765	1,564,018	6,185,958	7,749,976	10	4	39.48
6	500	3713	1,524,798	6,229,876	7,754,674	10	4	38.48
7	500	3704	1,584,251	6,337,849	7,922,100	10	4	39.17
8	500	3744	1,593,343	6,312,252	7,905,595	10	4	39.44
9	500	3692	1,524,499	6,072,466	7,596,965	10	4	38.33
10	500	3701	1,560,359	6,180,429	7,740,788	10	4	38.50

Table 5.7 Results of MCTFL problems using the single warehouse preference method

Problem #	# of Customers	# of SO items	Cost 1	Cost 2	Total Costs	# of WHs	# of Plants	CPU time (minutes)
1	500	3610	1,617,755	6,223,428	7,841,183	10	4	40.16
2	500	3802	1,788,158	6,748,562	8,536,720	10	4	41.39
3	500	3789	1,739,169	6,659,266	8,398,435	10	4	40.26
4	500	3794	1,798,202	6,842,822	8,641,024	10	4	40.28
5	500	3765	1,677,567	6,422,624	8,100,191	10	4	41.40
6	500	3713	1,662,846	6,499,809	8,162,655	10	4	40.50
7	500	3704	1,640,484	6,444,602	8,085,086	10	4	40.36
8	500	3744	1,659,982	6,429,611	8,089,593	10	4	41.07
9	500	3692	1,615,331	6,275,562	7,890,893	10	4	39.53
10	500	3701	1,668,252	6,406,288	8,074,540	10	4	40.27

Table 5.8 Results of MCTFL problems using MCTFL heuristic method

Problem #	# of Customers	# of SO items	Cost 1	Cost 2	Total Costs	# of WHs	# of Plants	CPU time (minutes)
1	500	3610	1,451,419	5,252,128	6,703,547	10	4	116.56
2	500	3802	1,523,395	5,849,263	7,372,658	10	4	149.29
3	500	3789	1,513,672	5,744,561	7,258,233	10	4	128.08
4	500	3794	1,581,236	5,334,156	6,915,392	10	4	141.21
5	500	3765	1,510,999	5,372,491	6,883,490	10	4	178.58
6	500	3713	1,479,166	5,637,848	7,117,014	10	4	120.00
7	500	3704	1,481,601	5,321,553	6,803,154	10	4	167.47
8	500	3744	1,520,652	5,243,388	6,764,040	10	4	120.02
9	500	3692	1,478,400	5,440,108	6,918,508	10	4	117.57
10	500	3701	1,511,526	5,511,449	7,022,975	10	4	129.09

Table 5.9 and 5.10 shows a comparison of the results for MCTFL problems that were solved using the shortest distance, the lowest transportation cost, the single warehouse preference, and the heuristic methods. The performance measure employed in this comparison was quality of solutions. As indicated by these two tables and Figure 5.1, MCTFL heuristic solutions for all 10 tests problems outperformed that of the other three methods. The shortest distance in the worst case came within 30.61% and in the best case came within 17.10% of the solution obtained by MCTFL heuristic. The lowest

transportation cost in the worst case came within 19.09% and in the best case came within 8.96% of the solution obtained by MCTFL heuristic. The single warehouse preference in the worst case came within 24.95% and in the best case came within 14.69% of the solution obtained by MCTFL heuristic. However, in all cases the other three methods outperformed MCTFL heuristic in the CPU time it took to find the best solution. MCTFL heuristic in worst case took 178.58 minutes and in the best case took 116.56 minutes to find the solution. While comparing among the three methods, the shortest distance in the worst case came within 9.83% and in the best case came within 5.08% of solution obtained by the lowest transportation cost. The shortest distance in the worst case came within 4.53% and in the best case came within 2.47% of solution obtained by the single warehouse preference. The single warehouse preference in the worst case came within 5.62% and in the best case came within 2.06% of solution obtained by the lowest transportation cost. However, all the three methods solved the problems within 38 to 42 minutes. Note that the percentage difference in solution equals ((Method II – Method I) ÷ Method I) * 100%.

Table 5.9 Comparison of MCTFL problems using shortest distance, lowest transportation cost, single warehouse preference and MCTFL heuristic methods

Problem #	Shortest Distance	Lowest Trans. Cost	Single Wh. Preference	MCTFL Heuristic	% Diff in Sol. Shortest vs. MCTFL	% Diff in Sol. Lowest vs. MCTFL	%Diff in Sol. Single Wh. Pref vs. MCTFL
1	8,066,965	7,549,139	7,841,183	6,703,547	20.34	12.61	16.97
2	8,876,408	8,082,176	8,536,720	7,372,658	20.40	9.62	15.79
3	8,647,323	8,094,247	8,398,435	7,258,233	19.14	11.52	15.71
4	9,032,531	8,235,634	8,641,024	6,915,392	30.61	19.09	24.95
5	8,300,569	7,749,976	8,100,191	6,883,490	20.59	12.59	17.68
6	8,426,920	7,754,674	8,162,655	7,117,014	18.41	8.96	14.69
7	8,324,879	7,922,100	8,085,086	6,803,154	22.37	16.45	18.84
8	8,368,134	7,905,595	8,089,593	6,764,040	23.72	16.88	19.60
9	8,101,625	7,596,965	7,890,893	6,918,508	17.10	9.81	14.05
10	8,309,173	7,740,788	8,074,540	7,022,975	18.31	10.22	14.97

Table 5.10 Comparison of MCTFL problems among shortest distance, lowest transportation cost, and single warehouse preference methods

Problem #	Shortest Distance	Lowest Trans. Cost	Single Wh. Preference	% Diff in Sol. Shortest vs. Lowest	% Diff in Sol. Shortest vs. Single Wh. Pref	%Diff in Sol. Single Wh. Pref vs. Lowest
1	8,066,965	7,549,139	7,841,183	6.86	2.88	3.87
2	8,876,408	8,082,176	8,536,720	9.83	3.98	5.62
3	8,647,323	8,094,247	8,398,435	6.83	2.96	3.76
4	9,032,531	8,235,634	8,641,024	9.68	4.53	4.92
5	8,300,569	7,749,976	8,100,191	7.10	2.47	4.52
6	8,426,920	7,754,674	8,162,655	8.67	3.24	5.26
7	8,324,879	7,922,100	8,085,086	5.08	2.97	2.06
8	8,368,134	7,905,595	8,089,593	5.85	3.44	2.33
9	8,101,625	7,596,965	7,890,893	6.64	2.67	3.87
10	8,309,173	7,740,788	8,074,540	7.34	2.91	4.31

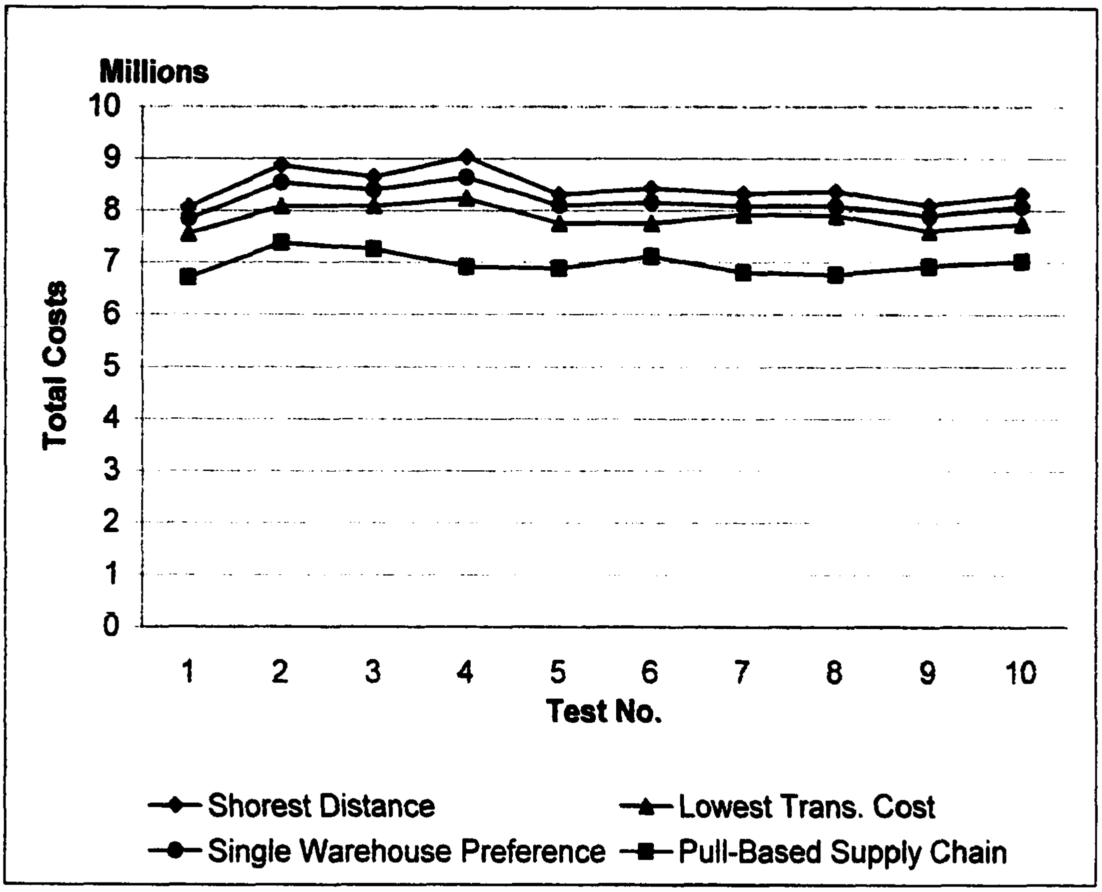


Figure 5.1 MCTFL total costs of 10 testing problems

Like in the previous comparisons, the quality of solution among the techniques was dominated by the MCTFL heuristic method while the solution time for the other three heuristics dominated the MCTFL heuristic. In other words, the three heuristics produced their best solutions in less time than the MCTFL heuristic. Again, as in the SCTFL case, if the quality of solution is the primary emphasis for decision making and computational time can be acquired at a reasonable cost, obviously, the MCTFL heuristic will be a preferred solution method. In today's industrial environment where computers are ubiquitous, the benefits of using the MCTFL heuristic over the three other heuristics will more than pay for the cost of computer time required to solve the problem.

5.4 Comparison of Results for PSCSP versus Other Two Heuristic Methods

So far, all tests performed were done based on facility location problem with either a single (SCTFL) or multiple products (MCTFL) on a long-term basis. In this section, the focus was shifted to weekly operations for a single product in what is known as the PSCSP problem. The operations mostly involved filling customers' orders, replenishing company's inventory, and manufacturing the products if needed. These decisions have huge impact on a company's total supply chain cost and ultimately affect later decisions over time. So, to determine how well this study's PSCSP heuristic would perform against other existing heuristic methodologies, 10 sets of simulated problems were used to perform the test. In each set of the problems, there were 13 weeks (quarter year) of customers' sales orders. In each week there were 30 to 100 sales orders. All sales orders were randomly generated from a pool of 500 customers. In order to reflect real life operation, all product inventory activities/movements were updated after each week. The results of the 10 problems that were solved using the shortest distance method are as given in Tables 5.11 to 5.20. The results of the same 10 problems using the lowest transportation cost heuristic are as given in Tables 5.21 to 5.30. The results of the same 10 problems using the PSCSP heuristic are as given in Table 5.31 to 5.40. These tables contain the following information:

- Column 1 shows the week identification number.
- Column 2 shows the total number of sales orders.
- Column 3 shows the total cost at warehouse and customer level, denoted as Cost 1.
- Column 4 shows the total cost at plant and warehouse level, denoted as Cost 2.
- Column 5 shows the total supply chain cost (Cost 1 plus Cost 2).
- Column 6 shows the number of actual warehouses used out of some possible number of warehouses.
- Column 7 shows the number of actual plants used out of some possible number of plants.
- Column 8 shows the total CPU time taken to arrive at the solution.

The main thing to note is that in all of the problems, PSCSP heuristic method generated the results with less number of warehouses and plants.

Table 5.11 PSCSP results of test no. 1 using the shortest distance method

Week No.	# of SO	Cost 1	Cost 2	Total Costs	# of Whs.	# of Plants	CPU Time (minutes)
1	61	47,594	37,852	85,446	9	1	0.41
2	30	38,116	26,380	64,496	9	1	0.17
3	51	48,554	95,919	144,473	10	2	0.23
4	55	49,666	47,890	97,556	10	1	0.33
5	47	43,179	91,363	134,542	9	2	0.50
6	56	48,072	87,320	135,392	9	1	0.35
7	50	44,044	119,119	163,163	9	2	0.29
8	54	48,259	68,747	117,006	10	2	0.28
9	47	45,939	92,888	138,827	10	2	0.46
10	55	43,967	105,584	149,551	8	1	0.33
11	61	57,418	129,972	187,390	10	3	0.51
12	44	46,497	84,985	131,482	10	2	0.42
13	54	47,904	93,001	140,905	10	2	0.31

Table 5.12 PSCSP results of test no. 2 using the shortest distance method

Week No.	# of SO	Cost 1	Cost 2	Total Costs	# of Whs.	# of Plants	CPU Time (minutes)
1	51	53,992	27,137	81,129	10	1	0.24
2	55	57,353	56,654	114,007	10	2	0.26
3	39	41,933	76,581	118,514	8	2	0.30
4	61	55,786	70,081	125,867	10	2	0.40
5	43	69,169	102,944	172,113	10	3	0.59
6	71	65,984	158,669	224,653	10	3	0.13
7	60	58,240	44,305	102,545	10	1	0.40
8	40	50,240	86,611	136,851	10	3	0.34
9	45	48,169	71,447	119,616	9	2	0.40
10	45	50,894	25,637	76,531	10	1	0.49
11	59	55,705	74,355	130,060	10	2	0.37
12	51	61,800	172,805	234,605	10	4	0.39
13	45	52,538	75,507	128,045	10	2	0.42

Table 5.13 PSCSP results of test no. 3 using the shortest distance method

Week No.	# of SO	Cost 1	Cost 2	Total Costs	# of Whs.	# of Plants	CPU Time (minutes)
1	70	72,501	89,968	162,469	10	1	0.15
2	50	50,683	98,976	149,659	8	2	0.23
3	34	46,060	58,165	104,225	10	3	0.21
4	56	60,210	92,359	152,569	10	2	0.34
5	56	58,262	80,485	138,747	10	3	0.35
6	60	60,935	190,504	251,439	9	3	0.39
7	56	56,951	41,040	97,991	10	1	0.35
8	38	46,848	85,973	132,821	9	2	0.28
9	47	50,396	85,806	136,202	9	3	0.45
10	60	62,017	109,957	171,974	10	2	0.39
11	58	57,277	87,491	144,768	10	2	0.35
12	55	56,906	121,562	178,468	10	2	0.32
13	49	48,016	123,816	171,832	8	3	0.26

Table 5.14 PSCSP results of test no. 4 using the shortest distance method

Week No.	# of SO	Cost 1	Cost 2	Total Costs	# of Whs.	# of Plants	CPU Time (minutes)
1	66	70,849	48,611	119,460	10	1	0.15
2	36	49,229	60,169	109,398	10	2	0.25
3	40	59,935	77,969	137,904	10	2	0.47
4	63	55,460	79,470	134,930	9	1	0.43
5	54	53,205	84,807	138,012	10	3	0.32
6	63	71,828	188,894	260,722	10	3	0.53
7	66	60,439	67,038	127,477	10	2	0.12
8	54	57,800	44,431	102,231	10	1	0.27
9	47	50,884	114,514	165,398	9	3	0.43
10	73	60,652	96,061	156,713	9	2	0.14
11	52	53,531	79,988	133,519	10	2	0.28
12	47	50,031	53,101	103,132	9	1	0.51
13	51	51,664	61,890	113,554	9	1	0.27

Table 5.15 PSCSP results of test no. 5 using the shortest distance method

Week No.	# of SO	Cost 1	Cost 2	Total Costs	# of Whs.	# of Plants	CPU Time (minutes)
1	58	71,675	107,785	179,460	10	1	0.36
2	36	55,254	106,237	161,491	10	3	0.22
3	51	67,756	169,818	237,574	10	2	0.24
4	57	67,332	161,227	228,559	9	3	0.36
5	61	75,230	170,038	245,268	10	3	0.39
6	52	84,765	196,605	281,370	10	2	0.41
7	60	72,422	180,129	252,551	10	4	0.39
8	46	62,408	87,798	150,206	10	2	0.44
9	41	60,628	97,166	157,794	10	3	0.33
10	56	69,738	220,652	290,390	10	3	0.33
11	54	81,288	165,388	246,676	10	2	0.44
12	54	66,237	167,473	233,710	9	3	0.32
13	63	90,486	218,139	308,625	10	2	0.52

Table 5.16 PSCSP results of test no. 6 using the shortest distance method

Week No.	# of SO	Cost 1	Cost 2	Total Costs	# of Whs.	# of Plants	CPU Time (minutes)
1	60	51,678	68,937	120,615	10	3	0.40
2	37	44,615	49,136	93,751	10	3	0.23
3	37	43,513	43,991	87,504	10	2	0.26
4	63	49,900	102,562	152,462	10	4	0.45
5	57	48,697	72,567	121,264	10	4	0.35
6	51	45,285	60,195	105,480	10	3	0.28
7	57	51,551	75,923	127,474	10	4	0.37
8	46	45,809	49,993	95,802	10	2	0.43
9	52	48,161	74,418	122,579	10	4	0.26
10	63	51,972	88,453	140,425	10	4	0.44
11	52	49,099	78,242	127,341	10	4	0.30
12	53	47,415	52,711	100,126	10	2	0.32
13	52	49,886	75,401	125,287	10	4	0.30

Table 5.17 PSCSP results of test no. 7 using the shortest distance method

Week No.	# of SO	Cost 1	Cost 2	Total Costs	# of Whs.	# of Plants	CPU Time (minutes)
1	55	49,730	69,168	118,898	10	3	0.45
2	44	45,964	61,535	107,499	10	4	0.35
3	40	50,501	88,385	138,886	10	4	0.45
4	59	45,998	90,877	136,875	9	3	0.39
5	54	48,769	86,681	135,450	10	3	0.31
6	74	51,963	105,964	157,927	10	4	0.16
7	60	51,051	85,051	136,102	10	4	0.42
8	43	47,234	70,618	117,852	10	3	0.38
9	36	42,234	38,711	80,945	10	2	0.26
10	50	48,510	82,755	131,265	10	4	0.29
11	52	46,577	53,501	100,078	10	2	0.30
12	64	48,897	91,513	140,410	10	4	0.13
13	50	47,963	84,885	132,848	10	3	0.27

Table 5.18 PSCSP results of test no. 8 using the shortest distance method

Week No.	# of SO	Cost 1	Cost 2	Total Costs	# of Whs.	# of Plants	CPU Time (minutes)
1	70	77,139	84,576	161,715	9	2	0.13
2	30	41,607	46,502	88,109	8	2	0.15
3	39	61,845	102,622	164,467	10	4	0.28
4	46	64,914	78,720	143,634	10	2	0.48
5	45	87,864	129,087	216,951	10	3	1.04
6	60	76,768	126,115	202,883	10	3	0.38
7	52	69,210	104,168	173,378	10	3	0.30
8	52	64,632	98,570	163,202	9	2	0.27
9	47	63,830	66,336	130,166	9	2	0.46
10	53	69,090	107,185	176,275	10	3	0.30
11	55	95,586	145,071	240,657	10	3	0.41
12	42	60,792	73,867	134,659	9	3	0.39
13	53	67,538	94,593	162,131	10	3	0.29

Table 5.19 PSCSP results of test no. 9 using the shortest distance method

Week No.	# of SO	Cost 1	Cost 2	Total Costs	# of Whs.	# of Plants	CPU Time (minutes)
1	60	58,420	48,106	106,526	10	1	0.39
2	37	51,477	16,337	67,814	10	1	0.24
3	55	60,208	177,775	237,983	10	3	0.27
4	55	58,241	61,353	119,594	10	2	0.33
5	38	47,161	29,719	76,880	10	2	0.35
6	50	55,306	89,546	144,852	10	2	0.28
7	65	60,348	167,036	227,384	10	4	0.11
8	50	53,513	43,944	97,457	10	1	0.25
9	56	56,437	79,958	136,395	10	2	0.29
10	61	55,505	84,439	139,944	9	2	0.40
11	47	62,347	116,446	178,793	10	3	1.05
12	49	55,606	94,317	149,923	10	1	0.27
13	49	51,760	49,982	101,742	10	2	0.25

Table 5.20 PSCSP results of test no. 10 using the shortest distance method

Week No.	# of SO	Cost 1	Cost 2	Total Costs	# of Whs.	# of Plants	CPU Time (minutes)
1	55	62,744	38,951	101,695	10	1	0.33
2	41	53,533	36,181	89,714	10	1	0.30
3	52	53,325	95,097	148,422	9	2	0.24
4	44	55,734	77,004	132,738	10	3	0.43
5	48	53,752	62,139	115,891	9	2	0.26
6	65	82,169	211,942	294,111	10	4	0.16
7	58	61,224	54,736	115,960	10	2	0.37
8	44	58,918	80,598	139,516	10	1	0.40
9	41	53,424	41,447	94,871	10	2	0.34
10	63	59,408	113,300	172,708	9	3	0.40
11	44	49,270	56,148	105,418	9	1	0.45
12	56	61,298	130,981	192,279	9	3	0.33
13	41	52,656	40,417	93,073	10	2	0.37

Table 5.21 PSCSP results of test no. 1 using the lowest transportation cost method

Week No.	# of SO	Cost 1	Cost 2	Total Costs	# of Whs.	# of Plants	CPU Time (minutes)
1	61	50,715	30,030	80,745	10	1	0.40
2	30	41,942	31,722	73,664	10	1	0.17
3	51	47,235	48,631	95,866	10	1	0.24
4	55	48,668	90,839	139,507	10	2	0.33
5	47	46,227	111,663	157,890	10	2	0.50
6	56	48,796	94,928	143,724	10	2	0.34
7	50	46,959	71,917	118,876	10	2	0.28
8	54	47,057	66,399	113,456	10	2	0.29
9	47	45,214	114,432	159,646	10	2	0.46
10	55	46,785	137,750	184,535	9	3	0.33
11	61	56,389	86,955	143,344	10	2	0.51
12	44	41,608	93,553	135,161	9	1	0.42
13	54	43,167	52,062	95,229	9	1	0.31

Table 5.22 PSCSP results of test no. 2 using the lowest transportation cost method

Week No.	# of SO	Cost 1	Cost 2	Total Costs	# of Whs.	# of Plants	CPU Time (minutes)
1	51	50,360	21,422	71,782	9	1	0.29
2	55	55,612	79,382	134,994	10	2	0.26
3	39	44,977	52,523	97,500	9	1	0.30
4	61	53,931	72,227	126,158	10	2	0.40
5	43	63,405	98,433	161,838	10	3	0.55
6	71	63,583	114,189	177,772	10	2	0.14
7	60	56,690	93,902	150,592	10	3	0.39
8	40	49,242	71,571	120,813	10	2	0.35
9	45	51,208	63,456	114,664	10	2	0.40
10	45	50,239	106,492	156,731	10	2	0.49
11	59	54,258	46,766	101,024	10	1	0.37
12	51	61,152	88,262	149,414	10	3	0.40
13	45	47,798	62,059	109,857	9	1	0.43

Table 5.23 PSCSP results of test no. 3 using the lowest transportation cost method

Week No.	# of SO	Cost 1	Cost 2	Total Costs	# of Whs.	# of Plants	CPU Time (minutes)
1	70	62,629	80,842	143,471	10	2	0.13
2	50	52,791	103,522	156,313	9	2	0.23
3	34	45,084	40,778	85,862	10	2	0.22
4	56	57,397	114,559	171,956	10	2	0.34
5	56	58,052	82,518	140,570	10	3	0.34
6	60	59,387	152,132	211,519	10	2	0.39
7	56	55,179	49,918	105,097	10	2	0.34
8	38	49,639	108,157	157,796	10	3	0.29
9	47	52,869	77,076	129,945	10	3	0.46
10	60	59,628	133,925	193,553	10	2	0.39
11	58	54,204	84,639	138,843	10	2	0.34
12	55	55,182	101,488	156,670	10	3	0.32
13	49	54,550	89,302	143,852	10	2	0.25

Table 5.24 PSCSP results of test no. 4 using the lowest transportation cost method

Week No.	# of SO	Cost 1	Cost 2	Total Costs	# of Whs.	# of Plants	CPU Time (minutes)
1	66	58,483	45,754	104,237	10	1	0.12
2	36	47,807	34,685	82,492	10	2	0.25
3	40	51,737	71,329	123,066	10	2	0.37
4	63	52,042	67,936	119,978	3	1	0.42
5	54	52,131	58,636	110,767	10	2	0.32
6	63	60,696	167,014	227,710	10	4	0.44
7	66	58,370	102,502	160,872	10	2	0.12
8	54	55,429	22,639	78,068	10	1	0.28
9	47	49,266	89,358	138,624	9	3	0.43
10	73	62,416	168,910	231,326	10	2	0.14
11	52	49,630	36,655	86,285	9	1	0.29
12	47	48,813	44,835	93,648	9	2	0.50
13	51	46,354	62,701	109,055	8	1	0.27

Table 5.25 PSCSP results of test no. 5 using the lowest transportation cost method

Week No.	# of SO	Cost 1	Cost 2	Total Costs	# of Whs.	# of Plants	CPU Time (minutes)
1	58	68,874	98,629	167,503	10	2	0.36
2	36	49,578	149,003	198,581	9	3	0.23
3	51	61,864	136,337	198,201	9	2	0.24
4	57	69,700	146,804	216,504	10	2	0.35
5	61	71,948	192,842	264,790	10	4	0.40
6	52	83,907	187,702	271,609	10	2	0.41
7	60	68,276	167,728	236,004	10	4	0.39
8	46	60,714	109,283	169,997	10	2	0.43
9	41	57,361	113,196	170,557	10	3	0.33
10	56	66,482	212,046	278,528	10	3	0.33
11	54	78,658	185,032	263,690	10	3	0.43
12	54	63,706	125,117	188,823	9	2	0.31
13	63	88,619	270,235	358,854	10	4	0.51

Table 5.26 PSCSP results of test no. 6 using the lowest transportation cost method

Week No.	# of SO	Cost 1	Cost 2	Total Costs	# of Whs.	# of Plants	CPU Time (minutes)
1	60	50,061	75,742	125,803	10	4	0.39
2	37	40,140	44,399	84,539	9	3	0.23
3	37	38,938	53,818	92,756	9	4	0.26
4	63	49,092	90,102	139,194	10	3	0.45
5	57	47,871	76,085	123,956	10	4	0.35
6	51	44,924	59,477	104,401	10	3	0.29
7	57	49,791	76,319	126,110	10	4	0.37
8	46	45,142	45,174	90,316	10	2	0.43
9	52	47,860	79,719	127,579	10	4	0.26
10	63	50,062	90,364	140,426	10	4	0.43
11	52	48,174	69,290	117,464	10	3	0.3
12	53	46,330	67,142	113,472	10	4	0.32
13	52	48,493	64,768	113,261	10	3	0.29

Table 5.27 PSCSP results of test no. 7 using the lowest transportation cost method

Week No.	# of SO	Cost 1	Cost 2	Total Costs	# of Whs.	# of Plants	CPU Time (minutes)
1	55	47,345	68,214	115,559	10	3	0.37
2	44	45,062	56,599	101,661	10	3	0.35
3	40	47,887	83,380	131,267	10	4	0.35
4	59	48,561	87,569	136,130	10	3	0.39
5	54	47,534	85,964	133,498	10	3	0.32
6	74	50,901	113,201	164,102	10	4	0.15
7	60	49,523	81,885	131,408	10	4	0.41
8	43	47,091	68,134	115,225	10	3	0.38
9	36	41,698	38,356	80,054	10	2	0.26
10	50	47,430	85,579	133,009	10	4	0.30
11	52	46,044	58,659	104,703	10	2	0.30
12	64	48,211	83,133	131,344	10	3	0.13
13	50	47,143	91,639	138,782	10	4	0.27

Table 5.28 PSCSP results of test no. 8 using the lowest transportation cost method

Week No.	# of SO	Cost 1	Cost 2	Total Costs	# of Whs.	# of Plants	CPU Time (minutes)
1	70	79,081	87,305	166,386	10	2	0.13
2	30	45,142	23,602	68,744	9	2	0.15
3	39	59,562	116,419	175,981	9	3	0.28
4	46	59,689	84,619	144,308	9	2	0.48
5	45	87,738	147,127	234,865	10	3	1.04
6	60	72,040	112,950	184,990	10	3	0.38
7	52	67,307	107,834	175,141	10	2	0.30
8	52	61,284	88,683	149,967	9	2	0.26
9	47	62,401	92,080	154,481	9	3	0.45
10	53	66,266	94,855	161,121	10	3	0.31
11	55	69,331	99,071	168,402	10	2	0.31
12	42	62,138	91,654	153,792	10	4	0.40
13	53	60,656	98,014	158,670	9	2	0.30

Table 5.29 PSCSP results of test no. 9 using the lowest transportation cost method

Week No.	# of SO	Cost 1	Cost 2	Total Costs	# of Whs.	# of Plants	CPU Time (minutes)
1	60	56,868	40,911	97,779	10	1	0.39
2	37	50,449	48,579	99,028	10	2	0.25
3	55	58,864	129,953	188,817	10	2	0.27
4	55	56,048	93,048	149,096	10	2	0.33
5	38	46,648	19,306	65,954	10	1	0.35
6	50	54,307	93,521	147,828	10	1	0.28
7	65	58,634	113,825	172,459	10	4	0.12
8	50	51,900	85,997	137,897	10	2	0.25
9	56	55,732	103,169	158,901	10	1	0.29
10	61	55,556	40,138	95,694	10	2	0.40
11	47	55,191	136,755	191,946	10	3	0.55
12	49	49,723	56,671	106,394	9	2	0.27
13	49	50,122	65,620	115,742	10	2	0.25

Table 5.30 PSCSP results of test no. 10 using the lowest transportation cost method

Week No.	# of SO	Cost 1	Cost 2	Total Costs	# of Whs.	# of Plants	CPU Time (minutes)
1	55	60,237	39,013	99,250	10	1	0.32
2	41	49,567	41,540	91,107	9	2	0.30
3	52	54,650	107,091	161,741	10	2	0.24
4	44	54,346	66,114	120,460	10	3	0.44
5	48	56,825	72,504	129,329	10	1	0.26
6	65	72,517	128,516	201,033	10	3	0.13
7	58	59,248	93,598	152,846	10	2	0.37
8	44	57,424	92,814	150,238	10	2	0.40
9	41	48,435	62,325	110,760	9	2	0.34
10	63	60,962	82,606	143,568	10	1	0.40
11	44	50,908	61,731	112,639	10	3	0.45
12	56	61,341	136,947	198,288	10	3	0.34
13	41	48,324	54,367	102,691	9	2	0.36

Table 5.31 PSCSP results of test no. 1 using PSCSP heuristic method

Week No.	# of SO	Cost 1	Cost 2	Total Costs	# of Whs.	# of Plants	CPU Time (minutes)
1	61	26,959	59,709	86,668	3	1	2.21
2	30	15,848	39,448	55,296	3	1	1.05
3	51	23,011	68,314	91,325	3	1	2.02
4	55	26,298	71,756	98,054	2	1	2.19
5	47	27,135	89,621	116,756	4	1	2.00
6	56	26,603	106,667	133,270	3	2	2.27
7	50	25,279	89,039	114,318	4	2	2.12
8	54	22,977	84,741	107,718	3	1	2.30
9	47	20,748	84,460	105,208	3	1	2.00
10	55	26,819	91,259	118,078	4	1	2.30
11	61	36,089	133,227	169,316	4	1	3.03
12	44	22,360	105,884	128,244	3	1	2.32
13	54	25,036	100,267	125,303	3	2	3.21

Table 5.32 PSCSP results of test no. 2 using PSCSP heuristic method

Week No.	# of SO	Cost 1	Cost 2	Total Costs	# of Whs.	# of Plants	CPU Time (minutes)
1	51	28,484	41,650	70,134	3	1	3.22
2	55	33,475	81,716	115,191	4	1	3.38
3	39	27,465	47,112	74,577	4	2	2.37
4	61	34,221	69,493	103,714	4	1	4.15
5	43	27,798	53,275	81,073	3	1	2.55
6	71	46,769	116,347	163,116	5	3	5.25
7	60	32,820	76,991	109,811	3	2	4.24
8	40	24,400	66,150	90,550	3	1	1.49
9	45	27,523	31,250	58,773	3	1	1.31
10	45	26,712	77,368	104,080	3	1	1.31
11	59	30,671	48,373	79,044	3	1	2.13
12	51	30,087	93,976	124,063	4	3	1.52
13	45	28,450	69,673	98,123	3	2	1.40

Table 5.33 PSCSP results of test no. 3 using PSCSP heuristic method

Week No.	# of SO	Cost 1	Cost 2	Total Costs	# of Whs.	# of Plants	CPU Time (minutes)
1	70	44,651	95,269	139,920	5	2	3.15
2	50	33,641	123,858	157,499	3	1	2.58
3	34	22,058	31,458	53,516	3	1	2.29
4	56	39,804	82,099	121,903	5	2	3.00
5	56	33,045	124,777	157,822	3	1	2.12
6	60	37,440	106,299	143,739	3	3	3.09
7	56	33,494	54,735	88,229	4	1	3.26
8	38	31,072	67,148	98,220	5	2	2.25
9	47	39,706	90,740	130,446	6	3	3.16
10	60	37,961	121,354	159,315	3	3	4.18
11	58	37,704	94,984	132,688	4	3	4.03
12	55	33,338	95,131	128,469	4	1	4.08
13	49	38,682	73,072	111,754	5	2	3.32

Table 5.34 PSCSP results of test no. 4 using PSCSP heuristic method

Week No.	# of SO	Cost 1	Cost 2	Total Costs	# of Whs.	# of Plants	CPU Time (minutes)
1	66	32,392	58,887	91,279	3	1	2.38
2	36	22,617	40,243	62,860	3	1	1.48
3	40	22,871	55,162	78,033	3	1	2.27
4	63	37,629	78,904	116,533	3	2	4.06
5	54	28,660	56,047	84,707	2	1	3.50
6	63	35,386	80,858	116,244	4	1	4.04
7	66	36,152	81,144	117,296	4	2	4.00
8	54	34,091	70,989	105,080	3	1	3.40
9	47	31,074	47,732	78,806	4	1	3.09
10	73	47,677	132,792	180,469	5	3	5.02
11	52	29,217	88,556	117,773	2	1	3.45
12	47	33,951	34,071	68,022	5	1	1.39
13	51	33,338	45,462	78,800	3	1	1.52

Table 5.35 PSCSP results of test no. 5 using PSCSP heuristic method

Week No.	# of SO	Cost 1	Cost 2	Total Costs	# of Whs.	# of Plants	CPU Time (minutes)
1	58	55,593	98,123	153,716	7	2	2.39
2	36	37,431	131,418	168,849	4	2	2.15
3	51	46,219	125,074	171,293	5	2	3.22
4	57	58,434	145,860	204,294	7	3	4.39
5	61	54,354	176,700	231,054	6	3	5.25
6	52	52,621	119,611	172,232	7	2	3.30
7	60	59,973	127,890	187,863	7	2	4.22
8	46	40,657	158,969	199,626	4	3	3.38
9	41	43,176	87,820	130,996	4	1	3.06
10	56	51,416	188,948	240,364	6	3	4.50
11	54	51,194	134,042	185,236	6	2	4.48
12	54	47,448	164,313	211,761	4	3	5.00
13	63	54,538	133,339	187,877	6	1	5.39

Table 5.36 PSCSP results of test no. 6 using PSCSP heuristic method

Week No.	# of SO	Cost 1	Cost 2	Total Costs	# of Whs.	# of Plants	CPU Time (minutes)
1	60	25,422	68,568	93,990	4	1	1.24
2	37	20,542	51,863	72,405	4	1	1.08
3	37	25,252	43,682	68,934	5	1	1.19
4	63	22,825	94,876	117,701	3	1	2.51
5	57	21,135	79,478	100,613	3	1	1.40
6	51	22,287	56,580	78,867	4	1	1.59
7	57	25,717	71,558	97,275	4	1	1.05
8	46	28,112	52,111	80,223	6	1	1.58
9	52	23,650	71,121	94,771	4	1	2.14
10	63	23,826	99,620	123,446	3	1	3.21
11	52	20,746	78,461	99,207	3	1	2.39
12	53	24,730	50,869	75,599	4	1	2.46
13	52	24,562	68,493	93,055	4	1	2.36

Table 5.37 PSCSP results of test no. 7 using PSCSP heuristic method

Week No.	# of SO	Cost 1	Cost 2	Total Costs	# of Whs.	# of Plants	CPU Time (minutes)
1	55	23,512	57,733	81,245	4	1	2.12
2	44	18,107	71,375	89,482	3	1	1.00
3	40	25,497	57,946	83,443	5	2	1.56
4	59	22,559	90,924	121,583	3	1	3.26
5	54	23,436	72,452	95,888	4	1	2.08
6	74	25,401	116,189	141,590	3	1	4.42
7	60	30,387	70,571	100,958	5	1	4.07
8	43	23,366	73,099	96,465	4	2	1.00
9	36	21,230	36,933	58,163	5	1	1.46
10	50	23,767	70,590	94,357	4	2	3.05
11	52	18,830	53,864	72,694	3	1	2.49
12	64	22,315	96,019	118,334	3	1	4.13
13	50	24,912	80,208	105,120	4	1	3.04

Table 5.38 PSCSP results of test no. 8 using PSCSP heuristic method

Week No.	# of SO	Cost 1	Cost 2	Total Costs	# of Whs.	# of Plants	CPU Time (minutes)
1	70	62,115	98,758	160,873	6	2	4.02
2	30	27,516	29,289	56,805	4	1	1.29
3	39	45,124	76,608	121,732	5	2	2.21
4	46	42,337	67,615	109,952	4	1	3.04
5	45	44,704	101,168	145,872	5	2	2.45
6	60	55,460	115,011	170,471	6	3	5.01
7	52	59,459	111,228	170,687	6	3	4.05
8	52	49,054	87,254	136,308	5	3	4.13
9	47	47,670	77,390	125,060	5	2	3.24
10	53	47,171	93,124	140,295	3	2	3.59
11	55	51,571	92,744	144,315	5	2	3.51
12	42	46,257	95,122	141,379	5	3	3.14
13	53	45,174	76,826	122,000	4	3	3.59

Table 5.39 PSCSP results of test no. 9 using PSCSP heuristic method

Week No.	# of SO	Cost 1	Cost 2	Total Costs	# of Whs.	# of Plants	CPU Time (minutes)
1	60	33,724	79,604	113,328	3	1	4.37
2	37	25,297	32,555	57,852	3	1	2.24
3	55	37,704	82,096	119,800	4	2	4.18
4	55	35,732	106,003	141,735	4	3	4.41
5	38	21,707	60,993	82,700	2	2	2.44
6	50	28,944	41,102	70,046	3	1	3.51
7	65	36,499	88,596	125,095	4	1	5.38
8	50	30,448	71,497	101,945	4	2	3.40
9	56	33,944	99,059	133,003	4	3	4.47
10	61	33,603	65,994	99,597	3	1	5.30
11	47	26,938	32,555	59,493	3	1	3.24
12	49	36,076	83,889	119,965	5	1	3.58
13	49	27,931	57,308	85,239	4	2	4.04

Table 5.40 results of test no. 10 using PSCSP heuristic method

Week No.	# of SO	Cost 1	Cost 2	Total Costs	# of Whs.	# of Plants	CPU Time (minutes)
1	55	38,469	39,763	78,232	4	1	5.01
2	41	29,623	56,177	85,800	3	1	3.12
3	52	33,666	65,307	98,973	2	1	4.25
4	44	31,332	80,236	111,568	4	1	3.39
5	48	36,718	67,193	103,911	4	3	4.34
6	65	51,319	78,754	130,073	5	2	6.04
7	58	45,654	96,052	141,706	4	2	5.32
8	44	34,849	83,263	118,112	4	1	3.41
9	41	29,915	61,425	91,340	4	2	3.45
10	63	45,480	70,084	115,564	4	2	6.10
11	44	32,926	112,914	145,840	4	1	3.48
12	56	39,727	62,948	102,675	3	1	5.04
13	41	31,820	39,476	71,296	4	2	3.52

Table 5.41 shows a comparison of the results for PSCSP total supply chain costs over 13 weeks that were solved using all three methods. The performance measure employed in this comparison was quality of solutions measured in cumulative supply chain cost over a 13 week period. As indicated in the table, the PSCSP heuristic solutions for all 10 tests

problems outperformed the shortest distance and the lowest transportation cost methods. The shortest distance method in the worst case came within 39.09% and in the best case came within 16.60% of the solution obtained by PSCSP heuristic. The lowest transportation cost method in the worst case came within 31.89% and in the best case came within 13.25% of solution obtained by PSCSP heuristic. However, in all cases the shortest distance method and the lowest transportation cost method outperformed PSCSP heuristic in terms of the CPU time required to find the best solution in each week. The PSCSP heuristic in the worst case took 6.10 minutes and in the best case took 3.12 minutes to find the solution (refer to Table 5.40). A comparison between the shortest distance method and the lowest transportation cost method shows that latter outperformed the former in nine out of the ten problems when the measure of performance is cost. There was not much difference in term of CPU time between these two methods. Note that the percentage difference in solution is computed according to the relationship ((Method II – Method I) ÷ Method I) * 100%.

Table 5.41 Comparison of the PSCSP weekly cumulative costs over 13 weeks using shortest distance, lowest transportation cost, and PSCSP heuristic methods

Problem #	Shortest Distance	Lowest Trans. Cost	PSCSP Heuristic	% Diff. in Sol. Shortest vs. Lowest	% Diff in Sol. Shortest vs. PSCSP	% Diff in Sol. Lowest vs. PSCSP
1	1,690,229	1,641,643	1,449,554	2.96	16.60	13.25
2	1,764,536	1,673,139	1,272,249	5.46	38.69	31.51
3	1,993,164	1,935,447	1,623,520	2.98	22.77	19.21
4	1,802,450	1,666,128	1,295,902	8.18	39.09	28.57
5	2,973,674	2,983,641	2,445,161	-0.33	21.61	22.02
6	1,520,110	1,499,277	1,196,086	1.39	27.09	25.35
7	1,635,035	1,616,742	1,259,322	1.13	29.83	28.38
8	2,158,227	2,096,848	1,745,749	2.93	23.63	20.11
9	1,785,287	1,727,535	1,309,798	3.34	36.30	31.89
10	1,796,396	1,773,950	1,395,090	1.27	28.77	27.16

Table 5.42 shows the weekly cumulative cost of all three methods based on the results of test problem number 10 presented in Table 5.20, 5.30, and 5.40. This table is also representative of the other test results shown in Tables 5.21 – 5.39. From the results, there is a trend.

Table 5.42 The weekly cumulative cost of all three methods based on test no.10

Week No.	Shortest Distance	Lowest Trans. Cost	PSCSP Heuristic
1	101,695	99,250	78,232
2	191,409	190,357	164,032
3	339,831	352,098	263,005
4	472,569	472,558	374,573
5	588,460	601,887	478,484
6	882,571	802,920	608,557
7	998,531	955,766	750,263
8	1,138,047	1,106,004	868,375
9	1,232,918	1,216,764	959,715
10	1,405,626	1,360,332	1,075,279
11	1,511,044	1,472,971	1,221,119
12	1,703,323	1,671,259	1,323,794
13	1,796,396	1,773,950	1,395,090

Figure 5.2 provides a perspective on how the cumulative total costs for the pull-based supply chain system may vary over time based on the results presented in Table 5.42. The three curves shown on the figure represent the results of the three algorithms presented. From Figure 5.2, it can be seen that the trend of the cumulative cost over the thirteen weeks are all similar except that the curve for the lowest transportation cost method and the shortest distance method are more closely aligned. In general, the lowest transportation cost method slightly produced better results than the shortest distance method. In fact, the two curves are almost parallel with a little gap between them starting from the first week. This means that as the number of weeks increases, the difference between the cumulative total cost between the two approaches also increased as one would expect. The percent difference in cumulative

cost between the two methods remained almost the same over time. On the other hand, when the cumulative cost trends of the three solution approaches are compared, the PSCSP curve has the smallest slope. The dominance of the PSCSP heuristic over its two rivals was evident by the second week. The gap in the quality of performance between the PSCSP heuristic and the shortest distance and the lowest transportation techniques grew over time. For an operational director or decision maker, the results mean that adopting PSCSP heuristic method to perform a pull-based supply chain system would improve the minimization of company supply chain cost and consequently, the overall system inventories. This result is intuitive.

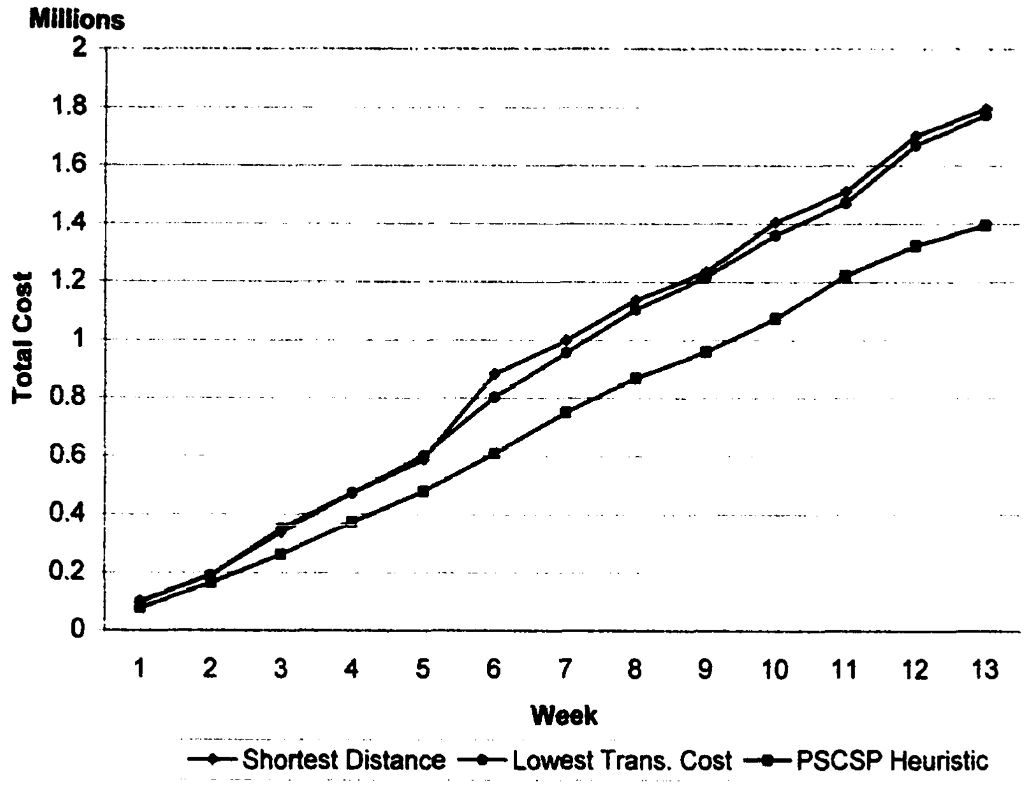


Figure 5.2 Graph of result from table 5.42

5.5 Comparison of Results for PSCMP versus Other Two Heuristic Methods

Like in the previous section, the focus was on a week-by-week operation except that this time multiple product system known as PSCMP problem was investigated. These operations again mostly involved filling customers' orders, replenishing company's inventories, and manufacturing the products as needed. These decisions make a huge impact on the company's total supply chain cost and ultimately affect later decisions over time as well. So, to determine how well this study's PSCMP heuristic would perform against other existing heuristic methodologies, 10 sets of simulated problems were used to perform the test. For each set of problems, there were 13 weeks or one quarter of a year of customers' sales orders that were considered. Each week consists of 300 sales orders and each sale order was made up of 1 to 5 sales order items. On the average there were 750 sales order items in each week. Sales order items were randomly generated from a pool of 15 product lines. All sales orders in each problem were randomly generated from the pool of 500 customers. The total number of sales order items for 13 weeks in each problem ranged from 9,000 to 10,500 sales order items. Again, to reflect the real life operation as closely as possible, all product inventory activities/movements were updated after each week. The results of the 10 problems that were solved using the shortest distance method are as given in Tables 5.43 to 5.52. The results of the same 10 problems using the lowest transportation cost method are as given in Tables 5.53 to 5.62. The results of the same 10 problems using the single warehouse preference method are as given in Tables 5.63 to 5.72. Finally, the results of the same 10 problems using PSCMP heuristic are as given in Table 5.73 to 5.82. These tables contain the following information:

- Column 1 shows the week identification number.

- Column 2 shows the total number of sales orders.
- Column 3 shows the total cost at warehouse and customer interface level, denoted as Cost 1.
- Column 4 shows the total cost at plant and warehouse interface level, denoted as Cost 2.
- Column 5 shows the total supply chain cost (Cost 1 plus Cost 2).
- Column 6 shows the number of actual warehouses used out of some possible number of warehouses. .
- Column 7 shows the number of actual plants used out of some possible number of plants.
- Column 8 shows the total CPU time to arrive at the solution.

An interesting feature to note is that in all of the problems, PSCMP heuristic method satisfied the orders with less number of warehouses and plants compared to the of PSCSP model

Table 5.43 PSCMP results of test no. 1 using the shortest distance method

Week No.	# of SO items	Cost 1	Cost 2	Total Costs	# of Whs.	# of Plants	CPU Time (minutes)
1	738	384,304	727,396	1,111,700	10	4	11.07
2	598	303,575	852,212	1,155,787	10	4	6.30
3	639	339,541	1,108,610	1,448,151	10	4	8.06
4	899	480,431	1,725,543	2,205,974	10	4	23.53
5	678	350,541	1,104,040	1,454,581	10	4	9.07
6	786	404,155	1,577,603	1,981,758	10	4	14.32
7	849	462,192	1,310,412	1,772,604	10	4	21.01
8	847	490,925	1,511,590	2,002,515	10	4	20.59
9	694	388,654	1,458,634	1,847,288	10	4	9.46
10	799	402,826	1,498,800	1,901,626	10	4	17.03
11	681	325,795	1,175,941	1,501,736	10	4	9.05
12	784	405,385	1,446,763	1,852,148	10	4	14.47
13	810	394,974	1,246,174	1,641,148	10	4	16.12

Table 5.44 PSCMP results of test no. 2 using the shortest distance method

Week No.	# of SO items	Cost 1	Cost 2	Total Costs	# of Whs.	# of Plants	CPU Time (minutes)
1	657	309,988	548,297	858,285	10	4	11.25
2	579	307,377	788,073	1,095,450	10	3	8.29
3	909	435,387	1,552,070	1,987,457	10	4	34.34
4	746	373,336	1,192,068	1,565,404	10	4	19.18
5	698	364,603	1,245,871	1,610,474	10	4	15.23
6	592	304,775	1,081,818	1,386,593	10	4	6.11
7	604	308,177	1,241,307	1,549,484	10	4	6.50
8	840	449,222	1,541,365	1,990,587	10	4	22.28
9	602	285,675	930,418	1,216,093	10	4	6.06
10	733	377,595	1,485,844	1,863,439	10	4	11.52
11	854	432,459	1,520,110	1,952,569	10	4	21.48
12	657	353,621	922,946	1,276,567	10	4	8.40
13	634	370,794	1,362,158	1,732,952	10	4	8.01

Table 5.45 PSCMP results of test no. 3 using the shortest distance method

Week No.	# of SO items	Cost 1	Cost 2	Total Costs	# of Whs.	# of Plants	CPU Time (minutes)
1	817	394,444	756,061	1,150,505	10	3	24.11
2	768	411,782	1,294,327	1,706,109	10	4	19.57
3	818	397,806	1,195,353	1,593,159	10	4	25.03
4	740	385,892	1,287,216	1,673,108	10	4	18.21
5	665	343,697	1,017,880	1,361,577	10	4	13.02
6	879	444,207	1,660,669	2,104,876	10	4	33.00
7	734	371,751	1,473,785	1,845,536	10	4	18.00
8	662	339,882	871,445	1,211,327	10	4	13.34
9	701	406,081	1,248,314	1,654,395	10	4	17.26
10	603	309,837	1,225,503	1,535,340	10	4	12.41
11	879	309,392	1,091,574	1,400,966	10	4	9.16
12	648	321,287	1,127,248	1,448,535	10	4	9.30
13	702	366,261	1,230,204	1,596,465	10	4	13.57

Table 5.46 PSCMP results of test no. 4 using the shortest distance method

Week No.	# of SO items	Cost 1	Cost 2	Total Costs	# of Whs.	# of Plants	CPU Time (minutes)
1	857	414,760	825,877	1,240,637	10	4	38.51
2	738	363,565	1,135,048	1,498,613	10	4	20.24
3	759	365,085	1,202,801	1,567,886	10	4	22.05
4	878	499,993	1,693,247	2,193,240	10	4	56.26
5	688	336,544	1,049,390	1,385,934	10	4	16.56
6	715	345,367	1,278,714	1,624,081	10	4	17.10
7	656	368,044	1,276,849	1,644,893	10	4	12.07
8	743	346,169	1,136,987	1,483,156	10	4	21.11
9	585	321,005	1,219,230	1,540,235	10	4	9.02
10	761	346,482	1,449,428	1,795,910	10	4	21.55
11	638	319,896	1,032,888	1,352,784	10	4	10.38
12	680	347,950	980,124	1,328,074	10	4	15.43
13	715	343,274	1,346,295	1,689,569	10	4	19.01

Table 5.47 PSCMP results of test no. 5 using the shortest distance method

Week No.	# of SO items	Cost 1	Cost 2	Total Costs	# of Whs.	# of Plants	CPU Time (minutes)
1	617	320,058	488,925	808,983	10	3	11.17
2	706	388,707	1,185,046	1,573,753	10	4	21.52
3	720	408,318	1,183,354	1,591,672	10	4	23.33
4	872	438,909	1,638,428	2,077,337	10	4	4.41
5	613	318,872	988,519	1,307,391	10	4	11.10
6	763	404,714	1,469,066	1,873,780	10	4	26.14
7	704	363,399	1,229,451	1,592,850	10	4	20.05
8	744	369,611	1,136,939	1,506,550	10	4	25.48
9	735	372,263	1,343,600	1,715,863	10	4	24.21
10	617	335,978	1,263,592	1,599,570	10	4	12.44
11	848	394,540	1,224,974	1,619,514	10	4	4.14
12	777	423,845	1,532,188	1,956,033	10	4	29.24
13	722	372,956	1,310,686	1,683,642	10	4	20.09

Table 5.48 PSCMP results of test no. 6 using the shortest distance method

Week No.	# of SO items	Cost 1	Cost 2	Total Costs	# of Whs.	# of Plants	CPU Time (minutes)
1	761	415,256	833,533	1,248,789	10	4	27.09
2	757	376,657	1,232,987	1,609,644	10	4	26.15
3	809	422,153	1,222,363	1,644,516	10	4	38.25
4	809	382,686	1,423,042	1,805,728	10	4	30.28
5	764	371,948	1,408,292	1,780,240	10	4	27.36
6	739	395,164	1,341,290	1,736,454	10	4	23.43
7	880	481,642	1,513,246	1,994,888	10	4	5.01
8	834	411,055	1,345,652	1,756,707	10	4	4.32
9	877	454,860	1,624,986	2,079,846	10	4	5.04
10	723	388,422	1,415,883	1,804,305	10	4	21.19
11	665	320,368	971,967	1,292,335	10	4	15.51
12	892	530,664	1,812,240	2,342,904	10	4	5.38
13	804	390,408	1,248,950	1,639,358	10	4	32.25

Table 5.49 PSCMP results of test no. 7 using the shortest distance method

Week No.	# of SO items	Cost 1	Cost 2	Total Costs	# of Whs.	# of Plants	CPU Time (minutes)
1	827	443,485	761,439	1,204,924	10	4	19.01
2	794	448,050	1,309,939	1,757,989	10	4	16.23
3	800	431,988	1,641,371	2,073,359	10	4	17.02
4	597	356,063	1,094,332	1,450,395	10	4	6.45
5	772	412,639	1,314,381	1,727,020	10	4	14.50
6	892	494,094	1,606,655	2,100,749	10	4	25.02
7	770	389,289	1,354,564	1,743,853	10	4	14.00
8	717	410,246	1,503,549	1,913,795	10	4	11.5
9	762	410,909	1,206,582	1,617,491	10	4	14.00
10	588	300,890	909,142	1,210,032	10	4	6.03
11	710	359,965	1,361,100	1,721,065	10	4	11.01
12	741	384,358	1,385,620	1,769,978	10	4	12.30
13	681	349,570	1,040,240	1,389,810	10	4	9.16

Table 5.50 PSCMP results of test no. 8 using the shortest distance method

Week No.	# of SO items	Cost 1	Cost 2	Total Costs	# of Whs.	# of Plants	CPU Time (minutes)
1	700	378,381	546,410	924,791	10	3	15.45
2	775	400,163	1,354,690	1,754,853	10	4	20.37
3	795	463,319	1,365,765	1,829,084	10	4	25.20
4	850	405,286	1,388,712	1,793,998	10	4	29.25
5	652	328,791	1,085,240	1,414,031	10	4	11.32
6	848	471,687	1,708,107	2,179,794	10	4	29.37
7	770	411,219	1,401,870	1,813,089	10	4	20.26
8	771	399,827	1,322,627	1,722,454	10	4	21.06
9	723	381,346	1,378,517	1,759,863	10	4	16.32
10	868	422,764	1,662,321	2,085,085	10	4	33.16
11	837	463,422	1,500,592	1,964,014	10	4	29.36
12	698	399,789	1,141,053	1,540,842	10	4	15.35
13	734	365,507	1,164,067	1,529,574	10	4	15.57

Table 5.51 PSCMP results of test no. 9 using the shortest distance method

Week No.	# of SO items	Cost 1	Cost 2	Total Costs	# of Whs.	# of Plants	CPU Time (minutes)
1	755	414,363	747,668	1,162,031	10	3	18.43
2	695	341,459	960,378	1,301,837	10	4	14.44
3	801	431,238	1,429,335	1,860,573	10	4	25.26
4	755	415,782	1,569,963	1,985,745	10	4	22.25
5	593	322,899	962,858	1,285,757	10	4	8.31
6	671	306,103	1,078,950	1,385,053	10	4	12.31
7	705	371,041	1,161,990	1,533,031	10	4	15.35
8	903	487,426	1,977,026	2,464,452	10	4	36.57
9	798	400,522	1,201,156	1,601,678	10	4	22.34
10	653	375,291	1,263,425	1,638,716	10	4	11.38
11	674	400,955	1,355,520	1,756,475	10	4	13.38
12	753	409,835	1,298,482	1,708,317	10	4	17.48
13	788	462,688	1,717,888	2,180,576	10	4	23.18

Table 5.52 PSCMP results of test no. 10 using the shortest distance method

Week No.	# of SO items	Cost 1	Cost 2	Total Costs	# of Whs.	# of Plants	CPU Time (minutes)
1	628	327,529	528,889	856,418	10	4	15.24
2	767	426,154	1,241,692	1,667,846	10	3	23.29
3	656	347,461	980,115	1,327,576	10	4	17.07
4	676	383,960	1,437,108	1,821,068	10	4	19.24
5	656	352,177	1,197,141	1,549,318	10	4	16.21
6	733	371,774	1,211,338	1,583,112	10	4	20.34
7	680	362,457	1,108,192	1,470,649	10	4	18.06
8	784	395,577	1,481,264	1,876,841	10	4	24.08
9	698	349,741	1,169,717	1,519,458	10	4	18.49
10	791	447,707	1,582,142	2,029,849	10	4	26.46
11	621	343,002	1,089,820	1,432,822	10	4	15.18
12	604	329,895	1,049,839	1,379,734	10	3	14.57
13	716	369,772	1,373,794	1,743,566	10	4	19.51

Table 5.53 PSCMP results of test no. 1 using the lowest transportation cost method

Week No.	# of SO items	Cost 1	Cost 2	Total Costs	# of Whs.	# of Plants	CPU Time (minutes)
1	738	340,837	727,658	1,068,495	10	4	11.12
2	598	269,380	777,603	1,046,983	10	4	6.16
3	639	303,816	1,047,989	1,351,805	10	4	7.27
4	899	429,629	1,728,408	2,158,037	10	4	22.18
5	678	313,191	1,041,390	1,354,581	10	4	8.46
6	786	363,258	1,424,833	1,788,091	10	4	14.06
7	849	386,512	1,315,001	1,701,513	10	4	19.49
8	847	406,913	1,498,199	1,905,112	10	4	19.16
9	694	336,229	1,299,594	1,635,823	10	4	9.16
10	799	356,785	1,426,115	1,782,900	10	4	16.09
11	681	306,373	1,074,908	1,381,281	10	4	9.01
12	784	359,449	1,411,303	1,770,752	10	4	14.13
13	810	355,866	1,439,401	1,795,267	10	4	15.45

Table 5.54 PSCMP results of test no. 2 using the lowest transportation cost method

Week No.	# of SO items	Cost 1	Cost 2	Total Costs	# of Whs.	# of Plants	CPU Time (minutes)
1	657	285,554	973,903	1,259,457	10	4	10.01
2	579	269,016	854,034	1,123,050	10	4	7.47
3	909	392,481	1,728,930	2,121,411	10	4	33.27
4	746	341,471	1,392,894	1,734,365	10	4	18.17
5	698	332,487	1,182,348	1,514,835	10	4	14.53
6	592	266,283	1,145,004	1,411,287	10	4	8.16
7	604	282,408	959,540	1,241,948	10	4	9.06
8	840	370,808	1,436,477	1,807,285	10	4	29.18
9	602	262,379	899,613	1,161,992	10	4	8.23
10	733	333,128	1,480,353	1,813,481	10	4	16.26
11	854	379,325	1,185,393	1,564,718	10	4	28.30
12	657	305,894	1,113,893	1,419,787	10	4	12.05
13	634	312,618	1,106,016	1,418,634	10	4	10.04

Table 5.55 PSCMP results of test no. 3 using the lowest transportation cost method

Week No.	# of SO items	Cost 1	Cost 2	Total Costs	# of Whs.	# of Plants	CPU Time (minutes)
1	817	361,119	738,925	1,100,044	10	3	23.36
2	768	346,515	1,160,099	1,506,614	10	4	18.16
3	818	346,893	1,315,348	1,662,241	10	4	24.15
4	740	333,288	1,190,869	1,524,157	10	4	17.31
5	665	310,978	932,454	1,243,432	10	4	11.55
6	879	389,606	1,726,930	2,116,536	10	4	31.32
7	734	318,444	1,073,701	1,392,145	10	4	16.06
8	662	304,764	1,072,547	1,377,311	10	4	12.29
9	701	338,831	1,304,309	1,643,140	10	4	15.15
10	603	285,673	978,144	1,263,817	10	4	9.04
11	879	394,455	1,648,393	2,042,848	10	4	29.32
12	648	290,310	928,219	1,218,529	10	4	9.51
13	702	322,980	1,272,067	1,595,047	10	4	14.05

Table 5.56 PSCMP results of test no. 4 using the lowest transportation cost method

Week No.	# of SO items	Cost 1	Cost 2	Total Costs	# of Whs.	# of Plants	CPU Time (minutes)
1	857	385,062	819,975	1,205,037	10	4	38.24
2	738	310,689	969,259	1,279,948	10	3	18.27
3	759	336,464	1,380,447	1,716,911	10	4	21.45
4	878	404,403	1,412,451	1,816,854	10	4	47.27
5	688	300,384	1,040,984	1,341,368	10	4	15.32
6	715	308,711	1,208,538	1,517,249	10	4	15.55
7	656	308,100	1,110,016	1,418,116	10	3	10.54
8	743	321,027	1,341,052	1,662,079	10	4	20.59
9	585	278,571	1,076,589	1,355,160	10	4	8.35
10	761	322,035	1,359,305	1,681,340	10	4	22.14
11	638	288,265	949,504	1,237,769	10	4	10.27
12	680	303,225	1,047,118	1,350,343	10	4	15.01
13	715	311,721	1,306,078	1,617,799	10	4	19.05

Table 5.57 PSCMP results of test no. 5 using the lowest transportation cost method

Week No.	# of SO items	Cost 1	Cost 2	Total Costs	# of Whs.	# of Plants	CPU Time (minutes)
1	617	287,093	1,029,199	1,316,292	10	4	9.01
2	706	323,785	1,382,677	1,706,462	10	4	18.24
3	720	336,641	1,125,705	1,462,346	10	4	19.00
4	872	388,759	1,613,103	2,001,862	10	4	4.30
5	613	278,398	962,397	1,240,795	10	4	9.20
6	763	364,069	1,498,913	1,862,982	10	4	22.43
7	704	327,239	1,158,168	1,485,407	10	4	18.34
8	744	323,450	1,295,801	1,619,251	10	4	23.54
9	735	337,949	1,185,510	1,523,459	10	4	23.05
10	617	286,188	976,309	1,262,497	10	4	11.21
11	848	372,630	1,553,227	1,925,857	10	4	4.13
12	777	368,652	1,232,624	1,601,276	10	4	27.49
13	722	339,894	1,144,243	1,484,137	10	4	19.40

Table 5.58 PSCMP results of test no. 6 using the lowest transportation cost method

Week No.	# of SO items	Cost 1	Cost 2	Total Costs	# of Whs.	# of Plants	CPU Time (minutes)
1	761	353,562	618,152	971,714	10	3	22.35
2	757	346,298	1,232,707	1,579,005	10	4	25.54
3	809	378,002	1,237,721	1,615,723	10	3	36.45
4	809	351,557	1,508,076	1,859,633	10	4	30.12
5	764	331,588	1,167,936	1,499,524	10	4	27.14
6	739	346,653	1,307,439	1,654,092	10	4	22.01
7	880	401,512	1,367,586	1,769,098	10	4	4.43
8	834	369,050	1,567,492	1,936,542	10	4	4.20
9	877	385,066	1,261,281	1,646,347	10	4	4.40
10	723	341,191	1,375,786	1,716,977	10	4	20.04
11	665	300,331	1,072,601	1,372,932	10	4	16.03
12	892	443,219	1,801,657	2,244,876	10	4	5.11
13	804	348,478	1,140,175	1,488,653	10	4	30.38

Table 5.59 PSCMP results of test no. 7 using the lowest transportation cost method

Week No.	# of SO items	Cost 1	Cost 2	Total Costs	# of Whs.	# of Plants	CPU Time (minutes)
1	827	374,327	728,467	1,102,794	10	4	17.16
2	794	368,668	1,197,260	1,565,928	10	4	15.11
3	800	370,879	1,523,842	1,894,721	10	4	16.48
4	597	294,576	1,008,051	1,302,627	10	4	6.41
5	772	364,890	1,135,684	1,500,574	10	4	14.55
6	892	415,162	1,546,421	1,961,583	10	4	24.54
7	770	351,041	1,274,976	1,626,017	10	4	13.24
8	717	339,709	1,350,009	1,689,718	10	4	11.14
9	762	376,030	1,246,836	1,622,866	10	4	13.52
10	588	252,400	946,398	1,198,798	10	4	6.01
11	710	320,182	1,397,649	1,717,831	10	4	10.38
12	741	337,601	1,276,726	1,614,327	10	4	12.52
13	681	287,991	907,408	1,195,399	10	4	10.42

Table 5.60 PSCMP results of test no. 8 using the lowest transportation cost method

Week No.	# of SO items	Cost 1	Cost 2	Total Costs	# of Whs.	# of Plants	CPU Time (minutes)
1	700	334,545	1,158,695	1,493,240	10	4	14.02
2	775	350,485	1,428,124	1,778,609	10	3	19.16
3	795	386,375	1,524,688	1,911,063	10	4	22.33
4	850	364,712	1,434,723	1,799,435	10	3	27.46
5	652	292,471	1,037,322	1,329,793	10	4	10.47
6	848	392,274	1,470,229	1,862,503	10	4	26.52
7	770	352,182	1,389,541	1,741,723	10	4	19.22
8	771	360,142	1,236,087	1,596,229	10	4	19.57
9	723	349,636	1,100,828	1,450,464	10	4	15.48
10	868	369,761	1,557,891	1,927,652	10	4	30.56
11	837	404,776	1,551,766	1,956,542	10	4	27.27
12	698	339,105	1,046,379	1,385,484	10	4	14.48
13	734	331,842	1,429,142	1,760,984	10	4	15.39

Table 5.61 PSCMP results of test no. 9 using the lowest transportation cost method

Week No.	# of SO items	Cost 1	Cost 2	Total Costs	# of Whs.	# of Plants	CPU Time (minutes)
1	755	342,615	737,330	1,079,945	10	4	16.23
2	695	311,933	898,490	1,210,423	10	4	13.37
3	801	343,183	1,344,370	1,687,553	10	4	22.03
4	755	372,618	1,253,537	1,626,155	10	3	19.23
5	593	281,957	954,678	1,236,635	10	4	8.12
6	671	285,725	1,341,866	1,627,591	10	4	12.05
7	705	309,855	1,055,756	1,365,611	10	4	13.57
8	903	416,886	1,564,033	1,980,919	10	3	33.55
9	798	357,453	1,335,804	1,693,257	10	4	21.22
10	653	325,879	1,171,517	1,497,396	10	3	10.40
11	674	329,592	1,168,888	1,498,480	10	4	12.28
12	753	363,763	1,555,726	1,919,489	10	4	16.59
13	788	366,029	1,255,414	1,621,443	10	4	12.36

Table 5.62 PSCMP results of test no. 10 using the lowest transportation cost method

Week No.	# of SO items	Cost 1	Cost 2	Total Costs	# of Whs.	# of Plants	CPU Time (minutes)
1	628	303,837	562,043	865,880	10	4	15.00
2	767	356,894	1,181,429	1,538,323	10	4	21.49
3	656	310,012	880,795	1,190,807	10	4	16.11
4	676	304,244	1,139,189	1,443,433	10	4	17.29
5	656	317,254	1,259,141	1,576,395	10	4	16.03
6	733	323,697	1,215,550	1,539,247	10	4	19.34
7	680	309,182	1,040,121	1,349,303	10	4	17.04
8	784	354,068	1,535,099	1,889,167	10	4	22.53
9	698	308,716	972,644	1,281,360	10	4	17.58
10	791	381,165	1,561,669	1,942,834	10	4	23.42
11	621	302,125	831,668	1,133,793	10	4	14.12
12	604	281,817	1,177,978	1,459,795	10	4	14.11
13	716	311,749	1,289,084	1,600,833	10	4	18.37

Table 5.63 PSCMP results of test no.1 using the single warehouse preference method

Week No.	# of SO items	Cost 1	Cost 2	Total Costs	# of Whs.	# of Plants	CPU Time (minutes)
1	738	346,903	717,726	1,064,629	10	4	11.13
2	598	284,266	865,881	1,150,147	10	4	6.41
3	639	312,351	972,537	1,284,888	10	4	8.07
4	899	441,705	1,832,034	2,273,739	10	4	25.51
5	678	327,619	1,047,402	1,375,021	10	3	9.41
6	786	367,439	1,366,267	1,733,706	10	4	15.24
7	849	420,123	1,518,020	1,938,143	10	4	19.50
8	847	452,734	1,592,929	2,045,663	10	4	20.54
9	694	351,317	1,195,027	1,546,344	10	3	9.44
10	799	371,890	1,423,585	1,795,475	10	4	16.54
11	681	303,962	1,103,694	1,407,656	10	4	8.56
12	784	372,683	1,429,679	1,802,362	10	4	14.41
13	810	357,391	1,514,802	1,872,193	10	4	16.05

Table 5.64 PSCMP results of test no.2 using the single warehouse preference method

Week No.	# of SO items	Cost 1	Cost 2	Total Costs	# of Whs.	# of Plants	CPU Time (minutes)
1	657	288,642	507,396	796,038	10	4	10.31
2	579	284,674	831,697	1,116,371	10	3	8.33
3	909	397,883	1,450,693	1,848,576	10	4	32.46
4	746	341,734	1,251,549	1,593,283	10	4	19.51
5	698	339,600	1,100,860	1,440,460	10	4	15.16
6	592	281,935	1,222,350	1,504,285	10	4	8.05
7	604	291,066	1,079,957	1,371,023	10	4	9.36
8	840	405,977	1,579,026	1,985,003	10	4	28.09
9	602	264,924	779,889	1,044,813	10	4	9.57
10	733	345,390	1,442,174	1,787,564	10	4	17.24
11	854	395,451	1,455,464	1,850,915	10	4	29.38
12	657	325,425	1,227,773	1,553,198	10	4	12.13
13	634	332,336	1,217,189	1,549,525	10	4	10.33

Table 5.65 PSCMP results of test no.3 using the single warehouse preference method

Week No.	# of SO items	Cost 1	Cost 2	Total Costs	# of Whs.	# of Plants	CPU Time (minutes)
1	817	365,460	751,734	1,117,194	10	3	24.46
2	768	381,491	1,227,419	1,608.910	10	4	18.51
3	818	369.554	1,293,466	1,663,020	10	4	27.09
4	740	353,535	1,221,229	1,574,764	10	4	19.32
5	665	317,382	1,195,432	1,512,814	10	4	15.29
6	879	405.612	1,514,244	1,919,856	10	4	31.56
7	734	340,980	1,198,302	1,539,282	10	4	15.09
8	662	314,085	1,015,877	1,329,962	10	4	14.52
9	701	364,100	1,431,342	1,795,442	10	4	16.26
10	603	288,870	894,356	1,183,226	10	4	10.13
11	879	396,551	1,783,625	2,180,176	10	4	20.00
12	648	292,946	847,343	1,140,289	10	3	7.01
13	702	343,278	1,349,091	1,692,369	10	4	10.11

Table 5.66 PSCMP results of test no.4 using the single warehouse preference method

Week No.	# of SO items	Cost 1	Cost 2	Total Costs	# of Whs.	# of Plants	CPU Time (minutes)
1	857	293,589	1,266,423	1,560,012	10	4	38.33
2	738	330.914	1,070,632	1,401,546	10	4	21.25
3	759	342,905	1,347,062	1,689,967	10	4	22.45
4	878	448,790	1,827,411	2,276,201	10	4	44.11
5	688	317,351	1,143,466	1,460,817	10	4	18.41
6	715	320,318	1,385,152	1,705,470	10	4	14.13
7	656	330,017	1,111,725	1,441,742	10	4	7.23
8	743	323,064	1,168,924	1,491,988	10	4	21.59
9	585	291,757	966,796	1,258,553	10	4	5.58
10	761	323,081	1,329,090	1,652,171	10	3	22.50
11	638	296,236	1,054,123	1,350,359	10	4	10.53
12	680	316,395	1,300,195	1,616,590	10	4	19.02
13	715	318,630	1,324,121	1,642,751	10	4	19.06

Table 5.67 PSCMP results of test no.5 using the single warehouse preference method

Week No.	# of SO items	Cost 1	Cost 2	Total Costs	# of Whs.	# of Plants	CPU Time (minutes)
1	617	302,665	548,803	851,468	10	3	9.29
2	706	352,290	1,056,703	1,408,993	10	4	19.20
3	720	369,237	1,096,759	1,465,996	10	4	20.05
4	872	403,105	1,724,727	2,127,832	10	4	4.10
5	613	291,281	952,853	1,244,134	10	4	9.39
6	763	374,571	1,404,249	1,778,820	10	4	22.59
7	704	336,376	1,084,227	1,420,603	10	4	19.09
8	744	338,061	1,452,522	1,790,583	10	4	22.52
9	735	348,620	1,255,789	1,604,409	10	4	22.14
10	617	309,627	1,053,687	1,363,314	10	4	11.02
11	848	371,370	1,360,411	1,731,781	10	4	5.36
12	777	393,292	1,543,225	1,936,517	10	4	26.25
13	722	343,383	1,147,637	1,491,020	10	4	18.25

Table 5.68 PSCMP results of test no.6 using the single warehouse preference method

Week No.	# of SO items	Cost 1	Cost 2	Total Costs	# of Whs.	# of Plants	CPU Time (minutes)
1	761	374,118	667,125	1,041,243	10	3	22.42
2	757	345,768	1,233,450	1,579,218	10	4	26.06
3	809	387,959	1,266,634	1,654,593	10	3	38.01
4	809	353,789	1,523,201	1,876,990	10	4	30.57
5	764	342,568	1,141,419	1,483,987	10	4	27.01
6	739	374,073	1,451,645	1,825,718	10	4	22.11
7	880	440,143	1,444,298	1,884,441	10	4	4.45
8	834	381,375	1,392,686	1,774,061	10	4	4.24
9	877	413,294	1,438,396	1,851,690	10	4	4.48
10	723	355,507	1,501,238	1,856,745	10	4	21.28
11	665	297,272	952,044	1,249,316	10	4	18.39
12	892	478,501	1,920,991	2,399,492	10	4	5.10
13	804	369,388	1,187,303	1,556,691	10	4	31.26

Table 5.69 PSCMP results of test no.7 using the single warehouse preference method

Week No.	# of SO items	Cost 1	Cost 2	Total Costs	# of Whs.	# of Plants	CPU Time (minutes)
1	827	402,330	751,480	1,153,810	10	4	17.56
2	794	403,488	1,333,743	1,737,231	10	4	15.57
3	800	391,600	1,522,035	1,913,635	10	4	16.49
4	597	319,616	956,582	1,276,198	10	4	6.29
5	772	380,456	1,305,406	1,685,862	10	4	14.30
6	892	441,626	1,682,865	2,124,491	10	4	24.24
7	770	364,007	1,262,919	1,626,926	10	4	13.45
8	717	373,683	1,301,157	1,674,840	10	4	11.41
9	762	377,974	1,318,937	1,696,911	10	4	13.43
10	588	275,582	985,176	1,260,758	10	4	6.01
11	710	331,693	1,325,743	1,657,436	10	4	10.27
12	741	353,996	1,352,195	1,706,191	10	4	12.14
13	681	319,619	1,104,813	1,424,432	10	4	9.04

Table 5.70 PSCMP results of test no.8 using the single warehouse preference method

Week No.	# of SO items	Cost 1	Cost 2	Total Costs	# of Whs.	# of Plants	CPU Time (minutes)
1	700	346,199	558,989	905,188	10	3	15.59
2	775	367,655	1,178,382	1,546,037	10	4	19.25
3	795	424,699	1,526,633	1,951,332	10	4	22.02
4	850	378,407	1,373,909	1,752,316	10	4	28.51
5	652	307,654	953,653	1,261,307	10	3	10.58
6	848	415,767	1,659,343	2,075,110	10	4	28.19
7	770	376,943	1,447,554	1,824,497	10	4	19.26
8	771	375,620	1,410,090	1,785,710	10	4	21.08
9	723	353,088	1,161,043	1,514,131	10	4	17.41
10	868	430,459	1,652,379	2,082,838	10	4	32.51
11	837	423,750	1,322,472	1,746,222	10	4	28.19
12	698	361,140	1,221,201	1,582,341	10	4	16.55
13	734	329,719	1,314,889	1,644,608	10	4	15.11

Table 5.71 PSCMP results of test no.9 using the single warehouse preference method

Week No.	# of SO items	Cost 1	Cost 2	Total Costs	# of Whs.	# of Plants	CPU Time (minutes)
1	755	378,849	743,363	1,122,212	10	4	17.28
2	695	320,650	933,916	1,254,566	10	4	13.18
3	801	394,703	1,483,151	1,877,854	10	4	23.48
4	755	372,272	1,261,405	1,633,677	10	4	19.50
5	593	296,444	907,771	1,204,215	10	4	8.12
6	671	287,195	1,326,759	1,613,954	10	4	12.36
7	705	336,429	1,239,743	1,576,172	10	4	14.38
8	903	445,405	1,680,123	2,125,528	10	4	33.13
9	798	374,866	1,372,791	1,747,657	10	4	22.25
10	653	339,283	1,019,055	1,358,338	10	4	10.57
11	674	361,068	1,389,191	1,750,259	10	4	13.02
12	753	381,568	1,518,379	1,899,947	10	4	15.35
13	788	420,067	1,406,280	1,826,347	10	4	12.07

Table 5.72 PSCMP results of test no.10 using the single warehouse preference method

Week No.	# of SO items	Cost 1	Cost 2	Total Costs	# of Whs.	# of Plants	CPU Time (minutes)
1	628	305,635	563,627	869,262	10	4	16.32
2	767	388,403	1,217,843	1,606,246	10	4	23.34
3	656	325,308	920,632	1,245,940	10	4	17.45
4	676	336,798	1,331,217	1,668,015	10	4	17.41
5	656	320,785	1,119,825	1,440,610	10	4	16.34
6	733	342,276	1,297,328	1,639,604	10	4	19.35
7	680	326,780	1,120,721	1,447,501	10	4	19.11
8	784	359,273	1,568,006	1,927,279	10	4	23.46
9	698	317,998	1,011,626	1,329,624	10	4	17.36
10	791	410,915	1,564,459	1,975,374	10	4	22.41
11	621	316,894	990,470	1,307,364	10	4	14.23
12	604	294,531	904,219	1,198,750	10	4	14.20
13	716	337,729	1,408,805	1,746,534	10	4	18.25

Table 5.73 PSCMP results of test no.1 using PSCMP heuristic method

Week No.	# of SO items	Cost 1	Cost 2	Total Costs	# of Whs.	# of Plants	CPU Time (minutes)
1	738	308,476	604,619	913,095	9	3	29.30
2	598	268,956	650,892	919,848	10	3	21.43
3	639	279,786	1,149,526	1,429,312	10	3	32.45
4	899	359,859	1,378,125	1,737,984	10	4	28.21
5	678	282,400	942,237	1,224,637	8	3	17.58
6	786	323,269	1,383,349	1,706,618	9	4	40.16
7	849	367,985	1,339,989	1,707,974	10	4	48.09
8	847	362,921	1,239,408	1,602,329	10	4	38.57
9	694	307,983	1,070,710	1,378,693	9	4	19.20
10	799	332,776	1,474,094	1,806,870	9	4	50.26
11	681	294,061	1,019,667	1,313,728	10	4	39.11
12	784	327,430	1,388,306	1,715,736	9	4	51.04
13	810	329,887	1,159,184	1,489,071	10	4	47.44

Table 5.74 PSCMP results of test no.2 using PSCMP heuristic method

Week No.	# of SO items	Cost 1	Cost 2	Total Costs	# of Whs.	# of Plants	CPU Time (minutes)
1	657	282,945	911,679	1,194,624	9	3	32.47
2	579	253,231	985,650	1,238,881	10	4	26.54
3	909	380,283	1,549,392	1,929,675	9	4	56.13
4	746	294,662	1,148,208	1,442,870	9	3	47.22
5	698	301,331	1,003,066	1,304,397	9	4	38.32
6	592	257,768	910,612	1,168,380	10	4	29.44
7	604	266,677	1,063,871	1,330,548	9	4	39.53
8	840	350,158	1,341,585	1,691,743	10	4	55.37
9	602	252,304	1,082,079	1,334,383	10	4	23.50
10	733	305,721	965,584	1,271,305	9	3	43.01
11	854	361,892	1,430,563	1,792,455	8	4	54.42
12	657	282,752	1,053,265	1,336,017	9	4	46.28
13	634	279,464	967,626	1,247,090	9	4	21.10

Table 5.75 PSCMP results of test no.3 using PSCMP heuristic method

Week No.	# of SO items	Cost 1	Cost 2	Total Costs	# of Whs.	# of Plants	CPU Time (minutes)
1	817	343,837	703,378	1,047,215	10	3	51.06
2	768	318,249	1,070,965	1,389,214	10	3	28.59
3	818	334,392	1,274,990	1,609,382	10	3	39.48
4	740	327,419	1,110,288	1,437,707	10	4	45.06
5	665	291,668	1,097,497	1,389,165	10	4	27.33
6	879	375,354	1,348,261	1,723,615	9	4	58.09
7	734	311,855	1,264,781	1,576,636	10	4	37.44
8	662	280,438	893,608	1,174,046	8	3	19.06
9	701	301,799	1,256,895	1,558,694	10	4	35.50
10	603	274,527	939,943	1,214,470	8	4	20.16
11	879	372,899	1,482,525	1,855,424	9	4	43.36
12	648	268,806	986,875	1,255,681	9	3	19.21
13	702	311,199	1,147,948	1,459,147	10	4	26.33

Table 5.76 PSCMP results of test no.4 using PSCMP heuristic method

Week No.	# of SO items	Cost 1	Cost 2	Total Costs	# of Whs.	# of Plants	CPU Time (minutes)
1	857	363,150	766,792	1,129,942	10	3	52.21
2	738	296,374	1,051,268	1,347,642	9	4	32.44
3	759	327,567	1,111,382	1,438,949	9	4	41.04
4	878	359,486	1,376,762	1,736,248	9	3	40.21
5	688	285,968	1,169,221	1,455,189	9	4	34.43
6	715	303,062	1,070,504	1,373,566	10	3	32.57
7	656	294,414	990,937	1,285,351	8	4	16.05
8	743	311,955	1,329,472	1,641,427	10	4	51.46
9	585	255,613	956,810	1,212,423	8	3	17.42
10	761	317,575	1,159,960	1,477,535	9	3	49.48
11	638	281,484	1,067,584	1,349,068	10	4	27.46
12	680	293,933	977,560	1,271,493	10	4	56.25
13	715	292,730	985,803	1,278,533	9	4	46.14

Table 5.77 PSCMP results of test no.5 using PSCMP heuristic method

Week No.	# of SO items	Cost 1	Cost 2	Total Costs	# of Whs.	# of Plants	CPU Time (minutes)
1	617	282,584	414,172	696,756	10	4	19.47
2	706	296,989	944,400	1,241,389	9	3	54.02
3	720	318,523	966,065	1,284,588	10	3	46.19
4	872	368,895	1,487,582	1,856,477	10	4	26.14
5	613	266,765	1,008,737	1,275,502	9	4	14.52
6	763	335,231	1,279,954	1,615,185	9	4	50.29
7	704	307,573	1,030,240	1,337,813	10	4	50.25
8	744	308,477	1,205,615	1,514,092	8	4	49.35
9	735	314,008	1,262,997	1,577,005	8	3	38.42
10	617	277,365	988,664	1,266,029	10	4	25.22
11	848	363,238	1,439,382	1,802,620	10	4	40.23
12	777	321,634	1,175,614	1,497,248	9	4	33.29
13	722	311,070	1,091,097	1,402,167	9	3	23.30

Table 5.78 PSCMP results of test no.6 using PSCMP heuristic method

Week No.	# of SO items	Cost 1	Cost 2	Total Costs	# of Whs.	# of Plants	CPU Time (minutes)
1	761	322,075	527,086	849,161	10	3	49.03
2	757	321,913	1,229,741	1,551,654	9	4	56.02
3	809	353,826	1,016,402	1,370,228	10	3	53.39
4	809	340,851	1,426,174	1,767,025	10	4	58.25
5	764	322,679	1,228,317	1,550,996	10	4	30.32
6	739	328,213	1,235,101	1,563,314	9	4	47.46
7	880	385,900	1,383,912	1,769,812	10	4	12.51
8	834	340,409	1,334,500	1,674,909	10	4	15.16
9	877	366,733	1,249,521	1,616,254	9	3	16.49
10	723	319,179	1,122,210	1,441,389	10	4	32.37
11	665	288,712	1,064,246	1,352,958	9	4	19.40
12	892	384,749	1,455,584	1,840,333	9	4	17.36
13	804	336,827	1,245,135	1,581,962	9	4	54.40

Table 5.79 PSCMP results of test no.7 using PSCMP heuristic method

Week No.	# of SO items	Cost 1	Cost 2	Total Costs	# of Whs.	# of Plants	CPU Time (minutes)
1	827	350,992	675,041	1,026,033	9	3	31.54
2	794	334,669	1,082,090	1,416,759	9	4	44.58
3	800	329,569	1,295,364	1,624,933	10	4	15.29
4	597	253,988	1,008,281	1,262,269	8	4	16.41
5	772	337,013	1,210,978	1,547,991	9	3	33.50
6	892	378,044	1,379,554	1,757,598	10	4	36.09
7	770	334,403	1,218,905	1,553,308	10	4	25.45
8	717	309,481	1,185,356	1,494,837	9	4	28.40
9	762	322,361	1,159,933	1,482,294	8	4	19.59
10	588	250,737	859,567	1,110,304	9	4	19.27
11	710	303,538	1,265,290	1,568,828	10	4	30.15
12	741	318,493	1,297,973	1,616,466	8	4	34.17
13	681	279,829	875,896	1,155,725	10	3	40.28

Table 5.80 PSCMP results of test no.8 using PSCMP heuristic method

Week No.	# of SO items	Cost 1	Cost 2	Total Costs	# of Whs.	# of Plants	CPU Time (minutes)
1	700	306,942	452,271	759,213	10	3	37.49
2	775	342,257	1,122,473	1,464,730	10	4	42.09
3	795	326,606	1,192,353	1,518,959	9	3	52.02
4	850	340,097	1,402,155	1,742,252	9	4	35.30
5	652	290,777	940,879	1,231,656	10	4	21.26
6	848	351,872	1,517,811	1,869,683	9	4	25.30
7	770	323,204	1,192,080	1,515,284	8	4	40.58
8	771	332,749	1,134,355	1,467,104	10	4	55.40
9	723	310,279	1,281,327	1,591,606	8	4	43.06
10	868	349,986	1,323,246	1,673,232	10	4	41.03
11	837	355,731	1,504,270	1,860,001	9	4	24.39
12	698	304,599	968,323	1,272,922	9	4	19.46
13	734	303,496	1,131,038	1,434,534	9	4	33.46

Table 5.81 PSCMP results of test no.9 using PSCMP heuristic method

Week No.	# of SO items	Cost 1	Cost 2	Total Costs	# of Whs.	# of Plants	CPU Time (minutes)
1	755	322,852	671,672	994,524	9	4	21.21
2	695	298,632	853,521	1,152,153	9	4	18.28
3	801	319,049	1,263,022	1,582,071	8	4	41.31
4	755	324,956	1,156,597	1,481,553	9	4	38.38
5	593	272,065	955,333	1,227,398	9	4	18.52
6	671	269825	1,292,007	1,561,832	8	4	17.23
7	705	302,138	1,070,308	1,372,446	9	4	48.43
8	903	384,346	1,449,158	1,833,504	9	4	31.15
9	798	337,744	1,193,738	1,531,482	10	4	45.38
10	653	298,588	1,006,541	1,305,129	10	4	28.44
11	674	288,904	1,172,242	1,461,146	10	4	31.02
12	753	325,228	1,177,576	1,502,804	9	4	33.43
13	788	344,996	1,236,746	1,581,742	9	4	25.19

Table 5.82 PSCMP results of test no.10 using PSCMP heuristic method

Week No.	# of SO items	Cost 1	Cost 2	Total Costs	# of Whs.	# of Plants	CPU Time (minutes)
1	628	279,743	428,343	708,086	9	3	36.50
2	767	325,826	1,108,838	1,434,664	9	4	49.18
3	656	291,735	1,046,054	1,337,789	9	3	50.36
4	676	277,634	952,929	1,230,563	10	4	31.07
5	656	292,039	1,028,338	1,320,377	9	4	30.01
6	733	304,068	1,382,907	1,686,975	8	4	29.45
7	680	283,774	901,117	1,184,891	8	4	30.39
8	784	322,595	1,294,514	1,617,109	10	4	52.37
9	698	286,815	978,872	1,265,687	8	4	30.06
10	791	326,708	1,258,442	1,585,150	10	4	30.30
11	621	289,760	1,070,165	1,359,925	9	4	19.24
12	604	257,312	970,016	1,227,328	9	3	19.42
13	716	296,195	1,192,485	1,488,680	9	4	41.38

Table 5.83 shows a comparison of the results for PSCMP total supply chain costs over 13 weeks that were solved using all four methods. The performance measure employed in this comparison was quality of solutions. As indicated by the table, PSCMP heuristic

solutions for all 10 tests problems outperformed that of the other three methods. The shortest distance in the worst case came within 17.63% and in the best case came within 8.52% of the solution obtained by PSCMP heuristic. The lowest transportation cost in the worst case came within 13.36% and in the best case came within 5.33% of solution obtained by PSCMP heuristic. The single warehouse preference in the worst case came within 14.17% and in the best case came within 6.34% of the solution obtained by PSCMP heuristic. However, in all cases the other three methods outperformed PSCMP heuristic in the CPU time it looks to find the best solution in each week. PSCMP heuristic in the worst case took 58.25 minutes and in the best case took 12.51 minutes to find the solution, please refer to Table 5.78. While comparing among the other three methods, namely, shortest distance, the lowest transportation cost, and the single warehouse preference methods in term of the quality of solutions, the lowest transportation cost outperformed the shortest distance method in all 10 test problems. The lowest transportation cost also outperformed the single warehouse preference method in 7 out of 10 test problems. The single warehouse preference outperformed the shortest distance in 9 out of 10 test problems. The shortest distance method in the worst case came within 9.08% and in the best case came within 1.44% of solution obtained by the lowest transportation cost method. The shortest distance method in the worst case came within 7.02% and in the best case came within −1.46% of solution obtained by the single warehouse preference. The single warehouse preference in the worst case came within 4.41% and in the best case came within −0.99% of solution obtained by the lowest transportation cost. There was not a significant difference in CPU time requirement among these three methods. Note that the percentage difference in solution is computed as ((Method II − Method I) ÷ Method I) * 100%.

Table 5.83 Comparison of the PSCMP weekly cumulative costs over 13 weeks using shortest distance, lowest transportation cost, single warehouse preference and PSCMP heuristic methods

No.	Shortest Distance (1)	Lowest Trans. Cost (2)	Single Wh. Pref. (3)	PSCMP Heuristic (4)	% Diff in Sol. (1) vs. (2)	% Diff in Sol. (1) vs. (3)	% Diff in Sol. (3) vs. (2)	% Diff in Sol. (1) vs. (4)	% Diff in Sol. (2) vs. (4)	% Diff in Sol. (3) vs. (4)
1	21,877,016	20,740,640	21,289,966	18,945,895	5.48	2.76	2.65	15.47	9.47	12.37
2	20,085,354	19,592,250	19,441,054	18,282,368	2.52	3.31	-0.77	9.86	7.16	6.34
3	20,281,898	19,685,861	20,257,304	18,690,396	3.03	0.12	2.90	8.52	5.33	8.38
4	20,345,012	19,199,973	20,548,167	17,997,366	5.96	-0.99	7.02	13.04	6.68	14.17
5	20,906,938	20,492,623	20,215,470	18,366,871	2.02	3.42	-1.35	13.83	11.57	10.06
6	22,735,714	21,355,116	22,034,185	19,929,995	6.46	3.18	3.18	14.08	7.15	10.56
7	21,680,460	19,993,183	20,938,721	18,617,345	8.44	3.54	4.73	16.45	7.39	12.47
8	22,311,472	21,993,721	21,671,637	19,401,176	1.44	2.95	-1.46	15.00	13.36	11.70
9	21,864,241	20,044,897	20,990,726	18,587,784	9.08	4.16	4.72	17.63	7.84	12.93
10	20,258,257	18,811,170	19,402,103	17,447,224	7.69	4.41	3.14	16.11	7.82	11.20

Table 5.84 The weekly cumulative cost of all four methods based on test problem no.10

Week No.	Shortest Distance	Lowest Trans. Cost	Single Wh. Preference	PSCMP Heuristic
1	856,418	865,880	869,262	708,086
2	2,524,264	2,404,203	2,475,508	2,142,750
3	3,851,840	3,595,010	3,721,448	3,480,539
4	5,672,908	5,038,443	5,389,463	4,711,102
5	7,222,226	6,614,838	6,830,073	6,031,479
6	8,805,338	8,154,085	8,469,677	7,718,454
7	10,275,987	9,503,388	9,917,178	8,903,345
8	12,152,828	11,392,555	11,844,457	10,520,454
9	13,672,286	12,673,915	13,174,081	11,786,141
10	15,702,135	14,616,749	15,149,455	13,371,291
11	17,134,957	15,750,542	16,456,819	14,731,216
12	18,514,691	17,210,337	17,655,569	15,958,544
13	20,258,257	18,811,170	19,402,103	17,447,224

Table 5.84 shows the weekly cumulative cost for all four methods based on the results of test problem 10 presented in Tables 5.52, 5.62, 5.72, and 5.82. The results of test problem 10 is shown as a representative of the results obtained with the other remaining 9

problems as shown in Tables 5.43 – 5.81. The pattern of the results of problem 10 is similar to those of problems 1 through 9.

Figure 5.3 provides a perspective on how the cumulative total costs of pull-based supply chain system in multiple product cases may vary as the number of weeks increases based on the results presented in Table 5.84. The four curves shown represent the four solution approaches tested. From Figure 5.3, it can be seen that the pattern for the cumulative cost are very similar for all the approaches. However, the cost pattern for the PSCMP method has the flattest slop and the shortest distance method the steepest slop, and consequently, the worst cost record. The curve patterns for the lowest transportation cost and the single warehouse preference methods lie between that of the PSCMP heuristic and the shortest distance method. It also can be seen that the gap between these two curves is very small, and with the two curves almost running parallel to one another from the eighth week through the thirteenth week, the end of the study period. This indicates that as the number of weeks increase, the performance difference between the two approaches will remain relatively stable. On the other hand, when the cumulative cost curve of the PSCMP heuristic relative to those of the other three methods is compared to the cumulative cost curve of the PSCSP method relative to its counterpart approaches, PSCMP curve shows the best slope. PSCMP heuristic has started to dominate the other three methods after fourth week as is evident on the graph. It can be seen that the gaps between PSCMP heuristic curve and the other three curves are much wider when the number of weeks increase. This means that the solution quality of PSCSP heuristic method keeps improving tremendously overtime as one might expect. For a decision maker, the results imply that the adoption of the PSCMP heuristic method for a pull-based supply chain system with multiple products offers the greatest opportunity for the overall minimization of cost when compared to the other approaches tested.

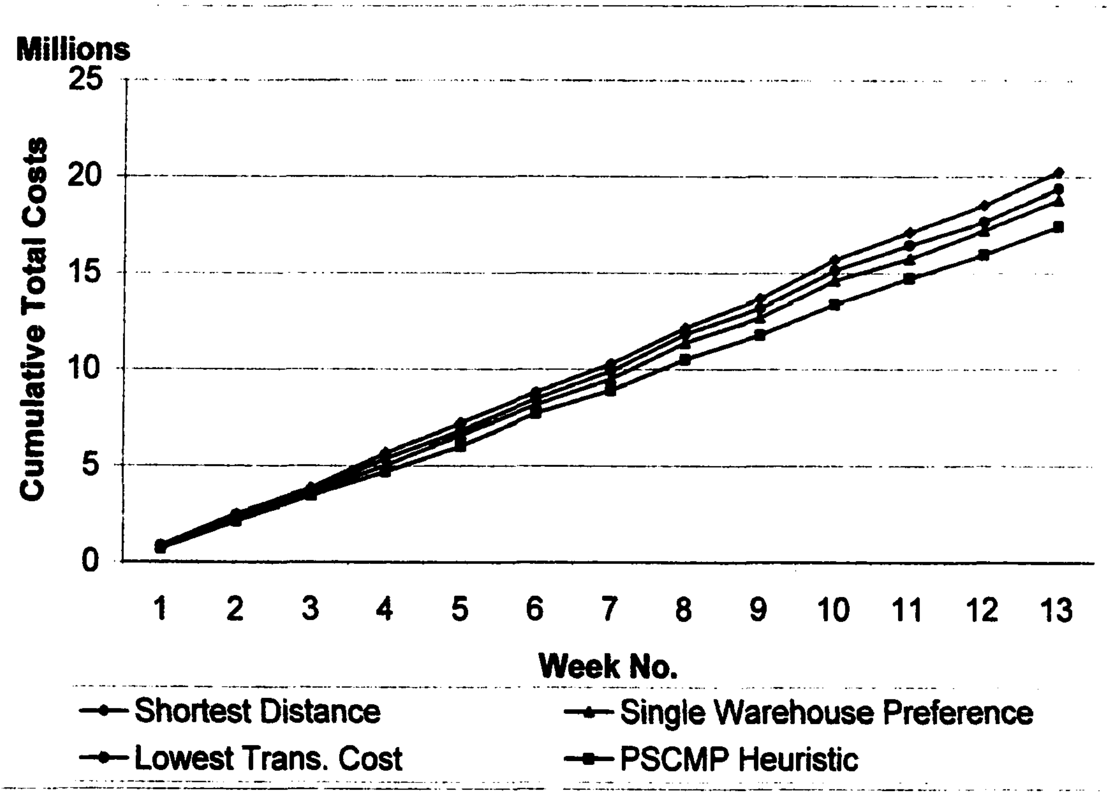


Figure 5.3 Graph of result from table 5.84

CHAPTER 6

SUMMARY AND CONCLUSION

In this study, the problem of integrating decisions along a customer demand driven or pull-based supply chain network involving single product or multiple products in a multi-echelon distribution system was addressed. Two main objectives were pursued in the study. The first objective was to present a general framework for the design and configuration of a supply chain network at the strategic and tactical planning levels for a single-product or multiple-product multiple-echelon supply chain system. The second objective was to develop a pull-based algorithm for the management of a pull-based supply chain system both for a single-product and multi-product multi-echelon system at the operational level. In both objectives, the procedures developed sought to minimize the system-wide supply chain cost. Four mixed integer linear programming models were developed in an effort to obtain optimal solution. The first model was based on the single-product capacitated two-echelon facility location problem (SCTFL). The second model was based on the multi-product capacitated two-echelon facility location problem (MCTFL). The third model was based on a pull-based supply chain for a single-product problem (PSCSP) and the last model was based on a pull-based supply chain for a multi-product problems (PSCMP). Because the mixed integer linear programming models were shown to be computationally intensive as the number of products, customers, warehouses, and manufacturing plants increased, decomposition heuristic procedures were developed to solve problems of practical sizes more efficiently.

The performances of the four mixed integer linear programming models and the heuristic procedures were demonstrated on four sets of randomly generated problems. Each set of problems consisted of 10 test problems, 500 customers, 10 distribution centers/warehouses, and 4 manufacturing plants. In the multi-product problems, MCTFL and PSCMP, the sets consisted of 15 products. All problems were solved via a program coded on Microsoft SQL/Visual Basic version 6.0, on a personal computer with Intel Pentium III-800 MHz CPU running under the Windows 2000 professional operating system. Quality of solution and CPU time of solution were the performance measures of interest. Also, three additional heuristic solution methods were used to check the quality of heuristic procedures: The three additional procedures were (1) the shortest distance method, (2) the lowest transportation cost method, and (3) the single warehouse preference method.

6.1 Summary of Results

The single product capacitated supply chain facility location, SCTFL, problem was tested and compared with other solution methods using 10 problems with randomly generated data. The results of the 10 problems using SCTFL heuristic were presented in Table 5.3. The results using the shortest distance and the lowest transportation cost methods were presented in Table 5.1 and 5.2, respectively. The comparison results between SCTFL heuristic and the two other methods were presented in Table 5.4. In all problems, the solutions obtained from the SCTFL heuristic consistently outperformed the solutions of the two other methods and the difference in solution was very significant. On the other hand, the CPU time required by the two other methods to solve the problems were significantly smaller than those obtained with the SCTFL heuristic.

The multiple products capacitated supply chain facility location, MCTFL, problem was also tested and compared with three other methods using another 10 test problems.

Each problem consisted of 15 products and 500 customers. The results obtained for the 10 problems using MCTFL heuristic were presented in Table 5.8. The results using the shortest distance, the lowest transportation cost, and the single warehouse preference methods were presented in Table 5.5 – 5.7. The comparison results were presented in Table 5.9 and 5.10. Based on the results obtained for the problems, the MCTFL heuristic consistently outperformed the three other methods. Also, in all problems, the difference in solution was very significant. In contrast, the CPU time required in solving the problems by the three other methods were significantly lower than those obtained using the MCTFL heuristic.

The results of the pull-based supply chain system for the single product case, PSCSP were also tested and compared against those obtained from two other methods using another set of 10 test problems. The results obtained from the PSCSP heuristic were presented in Table 5.31 – 5.40. The results of the shortest distance and the lowest transportation cost methods were presented in Tables 5.11 – 5.30. The comparison results were presented in Table 5.41 and 5.42. In all problems, the solution obtained under the PSCSP heuristic were consistently superior to those obtained from the two other methods. In all problems, the difference in solution was also very significant. However, when the CPU time required in solving the problems are used as the basis for performance comparison, the two other methods were much better than that of PSCSP heuristic. A profile of the performance of each method when used over a period of time was presented in Figure 5.2. The graph showed that a company that employs the PSCSP heuristic in managing its supply chain would enjoy much greater improvement in performance over time as compared to that which would be obtained using any of the two other methods

Finally, the pull-based supply chain in multiple product case, PSCMP, was tested and compared with three other methods using another set of 10 test problems. In each problem, there were 15 products and 500 customers involved. The results of PSCMP heuristic were presented in Tables 5.73 – 5.82. The results of the shortest distance method, the lowest transportation cost method, and the single warehouse preference method were presented in Tables 5.43 – 5.72. The comparison results of the four methods were presented in Table 5.41 and 5.42. In all problems, the solution under PSCMP heuristic consistently outperformed those of the three other methods. Also, in most problems, the difference in solution was very significant. However, the CPU time required by the PSCMP heuristic was much longer than those of the other three methods. Again, the performance profile of each solution method over time was presented in Figure 5.3. The graph indicated that a company's supply chain cost would enjoy the most improvement if the PSCMP heuristic is used as against using any of the three other techniques tested.

6.2 Conclusion

In this research the problem of integrating decisions in a supply chain system at the strategic, tactical, and operational levels was addressed. Four mathematical models along with heuristic solution algorithms for solving the problems were developed. The effectiveness of the heuristic algorithms were demonstrated by solving some sets of test problems. The results of the test problems also suggest that the heuristics are effective in solving fairly large size problems with reasonable computational time. One of the most important features of the heuristic algorithms is that they are also suitable for use in any binary location and allocation problems. Other important features of the algorithms include the ease of implementation, user friendliness, ability to provide a systematic way for improving and tightening a company's supply chain, ability to reduce the total supply chain cost in filling customers' orders, ability for planning and replenishment of systemwide inventories, and the planning of systemwide production. The contributions of the research in the area of supply chain management are significant and are detailed in section 1.5.

It can be concluded that the heuristic algorithms developed for the supply chain network configuration in both the single and multiple product cases, SCTFL and MCTFL, produced superior performance as compared to the other techniques that were tested. Although the SCTFL and MCTFL algorithms require considerable more time to solve problems, when the computer time is properly weighted against the resulting cost savings that is derived in using the algorithm, the use of the SCTFL and MCTFL heuristics would still prove to be the preferred choice for application in a supply chain system. The choice of SCTFL and MCTFL could be further strengthen by the fact that although an optimal solution is not guaranteed, SCTFL and MCTFL produce very good solutions and can be implemented quite easily.

It can also be concluded that the heuristic algorithms developed for the pull-based supply chain system involving single and multiple products, PSCSP and PSCMP, generate far better results than their counterpart techniques that were also tested. The same conclusion can also be drawn even after considering the effect of the larger computational time required by the heuristics. Like SCTFL and MCTFL, the choice of the PSCSP and PSCMP over their competitors tested is strengthened by the fact that they (i.e., the PSCSP and PSCMP heuristics) produce very good solutions and can be easily implemented. More importantly, they can be used as weekly execution tool.

6.3 Insights Gained

When using SCTFL and PSCSP, the number of warehouses and plants played a critical role in overall solutions. In all problems, SCTFL and PSCSP heuristics produced solutions that required fewer warehouses and plants as compared to the solutions obtained with the shortest distance and the lowest transportation cost methods. This is because SCTFL and PSCSP methods do consider warehouse and plant fixed costs in their assignments of orders. This implies the use of SCTFL and PSCSP can produce significant cost savings in systems with high fixed facility costs.

Unlike SCTFL and PSCSP, the number of overall facilities required for the solutions obtained under the MCTFL and PSCMP algorithms were not much different from those obtained with the other heuristic methods tested. This is because the aggregation of different product demands takes place at both the warehouse and plant levels.

Judging from the results obtained from the test problems, one is more likely to obtain a better solution in terms of total supply chain cost with less CPU time for problems with fewer number of customers and larger number of products per customer as compared to problems with larger number of customers and fewer number of products per customer. In other words, it is easier to obtain good solutions for problem with fewer number of customers and large number of products than for problems with a larger number of customers and fewer number of products.

6.4 Possible Extensions

The quest for optimal solutions to supply chain configuration and pull-base supply chain problems of large sizes still remains a formidable task; the problem is not close to being solved. Because of the computational complexity involved in obtaining optimal solutions, the trend toward the acceptance of near optimal solutions is increasing.

The supply chain network for this research represented a scenario where two echelon systems were integrated and evaluated to satisfy customer demands. Furthermore, the system evaluated was operated under several limiting assumptions: there were known customer demands, all distribution centers were resupplied only from the plants, there were no late shipments, and importantly only a single transportation mode was used. Further research might address these limitations by relaxing them separately or in combinations. The benefits that might be derived from such relaxation include improvement of customer service standards, improvement of inventory positioning, and better transportation system selection and routing. Also, not considered in this study was express orders or some sort of priority orders. As anyone in industry can attest to, priority orders are common in practice and therefore ought to be considered in the planning of supply chain systems. However, the implementation of this extension will mean the development of more complex models that explicitly capture stochastic events.

APPENDIX A
EXAMPLE OF CUSTOMER ORDERS

Report No.003 Customer Order Sorted by Sales Order Numbers

SO. No.	Customer Name	Product Name	Order Qty.	Amount	Promised Date
19	A & L SUPPLY				
		ADMIRAL/WS16	6.00	$324.00	01 / 01 / 2001
		BIOGAINFE/WS20	21.00	$1,491.00	01 / 01 / 2001
				$1,815.00	
20	SEED BIOTICS				
		ADMIRALW/WS16	38.00	$2,204.00	01 / 01 / 2001
		AG36/D055	3.00	$1,041.00	01 / 01 / 2001
		AG36/GL04	72.00	$2,808.00	01 / 01 / 2001
				$6,053.00	
21	WILBUR ELLIS				
		AG145/GL04	14.00	$588.00	01 / 01 / 2001
		BIOGAINFECAW/WS20	18.00	$1,728.00	01 / 01 / 2001
				$2,316.00	
22	TURF SUPPLY COMPANY				
		AG145/QT01	96.00	$1,728.00	01 / 01 / 2001
		BIOGAIN/JR12	19.00	$1,995.00	01 / 01 / 2001
		BIOGAINFE/WS20	10.00	$710.00	01 / 01 / 2001
				$4,433.00	
23	M.D. PRICE				
		AG36/GL04	75.00	$2,925.00	01 / 01 / 2001
				$2,925.00	
24	MIDDLE SMITHFIELD MATERIALS				
		ADMIRAL/D030	2.00	$766.00	01 / 01 / 2001
		ADMIRALW/WS16	27.00	$1,566.00	01 / 01 / 2001
				$2,332.00	
25	CHEM TECH				
		ADMIRAL/D030	7.00	$2,681.00	01 / 01 / 2001
		AG36/GL04	68.00	$2,652.00	01 / 01 / 2001
		BIOGAIN/WS40	17.00	$901.00	01 / 01 / 2001

Printed Date: 10/23/2002

Report No.003 **Customer Order Sorted by Sales Order Numbers**

SO. No.	Customer Name	Product Name	Order Qty.	Amount	Promised Date
				$6,234.00	
26	TMX INDUSTRIES				
		ADMIRAL/GL04	44.00	$2,420.00	01 / 01 / 2001
		AG36/GL04	63.00	$2,457.00	01 / 01 / 2001
				$4,877.00	
27	SPRAY TECH MANUFACTURING				
		AG36/G202	48.00	$2,976.00	01 / 01 / 2001
		AG36/QT12	40.00	$3,120.00	01 / 01 / 2001
		AVO1090/D030	8.00	$3,832.00	01 / 01 / 2001
				$9,928.00	
28	RITZVILLE CHEMICALS INC				
		ADMIRAL/WS16	44.00	$2,376.00	01 / 01 / 2001
				$2,376.00	
29	WOODCYCLE INC				
		AG36/D055	8.00	$2,776.00	01 / 01 / 2001
		AVO1090/D030	6.00	$2,874.00	01 / 01 / 2001
		BIOGAINCA/WS40	38.00	$2,052.00	01 / 01 / 2001
				$7,702.00	
30	INTERNATIONAL RESOURCE GROU				
		BIOGAINCA/WS40	44.00	$2,376.00	01 / 01 / 2001
				$2,376.00	
31	F & G REALTY				
		ADMIRAL/D030	8.00	$3,064.00	01 / 01 / 2001
		ADMIRAL/GL04	97.00	$5,335.00	01 / 01 / 2001
				$8,399.00	
32	WILLIAMSBURG RECYCLING - DO N				
		AG36/QT12	20.00	$1,560.00	01 / 01 / 2001
		BIOGAINCAW/WS40	8.00	$640.00	01 / 01 / 2001

Printed Date: 10/23/2002

Report No.003 Customer Order Sorted by Sales Order Numbers

SO. No.	Customer Name	Product Name	Order Qty.	Amount	Promised Date
		BIOGAINFECA/WS20	14.00	$980.00	01 / 01 / 2001
				$3,180.00	
33	SPS TRANSPORTATION LTD				
		AG145/GL04	21.00	$882.00	01 / 01 / 2001
				$882.00	
34	ARTISAN LANDSCAPING				
		BASOILBLUE25/D005	4.00	$3.532.00	01 / 01 / 2001
				$3,532.00	
35	POCONO TURF SUPPLY CO INC				
		ADMIRAL/D030	9.00	$3,447.00	01 / 01 / 2001
				$3,447.00	
36	KIMBALL TREE SERVICE				
		ADMIRAL/D030	7.00	$2,681.00	01 / 02 / 2001
		BASOILBLUE25/D005	4.00	$3.532.00	01 / 02 / 2001
				$6,213.00	
37	SUPERIOR SERVICES				
		AG145/QT01	150.00	$2.700.00	01 / 02 / 2001
		BIOGAINFE/WS20	18.00	$1.278.00	01 / 02 / 2001
				$3,978.00	
38	NEW ENGLAND BARK MULCH				
		AG36/QT01	291.00	$2.328.00	01 / 02 / 2001
				$2,328.00	
39	BRADDY FARM SUPPLY & EQUIPM				
		AG145/D055	10.00	$3,470.00	01 / 02 / 2001
		AG36/QT01	206.00	$1,648.00	01 / 02 / 2001
				$5,118.00	

Printed Date: 10/23/2002

Report No.003 **Customer Order Sorted by Sales Order Numbers**

SO. No.	Customer Name	Product Name	Order Qty.	Amount	Promised Date
40	HOLLISTON SAND COMPANY				
		AG145/QT12	40.00	$3,360.00	01 / 02 / 2001
		BIOGAINFECA/WS20	11.00	$770.00	01 / 02 / 2001
				$4,130.00	
41	BJORNSON OIL COMPANY				
		BIOGAINFE/WS20	37.00	$2,627.00	01 / 02 / 2001
				$2,627.00	
42	ARBORCHEM PRODUCTS CO				
		AG36/D055	5.00	$1,735.00	01 / 02 / 2001
		AVO1090/D030	9.00	$4,311.00	01 / 02 / 2001
		BASOILBLUE25/D005	5.00	$4,415.00	01 / 02 / 2001
				$10,461.00	
43	IOWA STATE UNIVERSITY ATHLETI				
		ADMIRAL/WS16	31.00	$1,674.00	01 / 02 / 2001
		AG36/G202	37.00	$2,294.00	01 / 02 / 2001
		BASOILBLUE25/D005	3.00	$2,649.00	01 / 02 / 2001
				$6,617.00	
44	MINNESOTA DISTRIBUTING				
		AG145/QT01	141.00	$2,538.00	01 / 02 / 2001
		AG36/G202	34.00	$2,108.00	01 / 02 / 2001
		BIOGAIN/WS40	45.00	$2,385.00	01 / 02 / 2001
				$7,031.00	
45	BEST SAND CORPORATION				
		AG36/GL04	34.00	$1,326.00	01 / 02 / 2001
		BASOILBLUE25/D005	5.00	$4,415.00	01 / 02 / 2001
				$5,741.00	
46	BOSS SUPPLY INC				
		AG145/D055	9.00	$3,123.00	01 / 02 / 2001

Printed Date: 10/23/2002

Report No.003 **Customer Order Sorted by Sales Order Numbers**

SO. No.	Customer Name	Product Name	Order Qty.	Amount	Promised Date
				$3,123.00	
47	ZUMBRO VALLEY FORESTRY				
		AG36/D055	5.00	$1,735.00	01 / 02 / 2001
		BIOGAINCA/WS40	50.00	$2,700.00	01 / 02 / 2001
				$4,435.00	
48	VIRGINIA GROUND COVERS				
		AG36/GL04	51.00	$1,989.00	01 / 02 / 2001
				$1,989.00	
49	BROOKVILLE WOOD PRODUCTS				
		AG145/G202	8.00	$496.00	01 / 02 / 2001
		AG145/GL06	6.00	$372.00	01 / 02 / 2001
		AG36/G202	35.00	$2,170.00	01 / 02 / 2001
				$3,038.00	
50	CTC LLC				
		AG36/G202	16.00	$992.00	01 / 02 / 2001
		AG36/GL06	19.00	$1,140.00	01 / 02 / 2001
		BIOGAINCA/WS40	54.00	$2,916.00	01 / 02 / 2001
				$5,048.00	
51	E.H. GRIFFITH INC				
		ADMIRAL/D030	3.00	$1,149.00	01 / 02 / 2001
		AG145/GL04	51.00	$2,142.00	01 / 02 / 2001
		BASOILBLUE/GL04	12.00	$1,188.00	01 / 02 / 2001
				$4,479.00	
52	AMERICAN CLAY WORKS AND SU				
		AG145/D055	3.00	$1,041.00	01 / 03 / 2001
		AVO1090/D030	3.00	$1,437.00	01 / 03 / 2001
				$2,478.00	
53	FORSHAW DISTR. INC				

Printed Date: 10/23/2002

Report No.003 **Customer Order Sorted by Sales Order Numbers**

SO. No.	Customer Name	Product Name	Order Qty.	Amount	Promised Date
		ADMIRAL/WS16	7.00	$378.00	01 / 03 / 2001
		BIOGAIN/JR12	16.00	$1,680.00	01 / 03 / 2001
		BIOGAINFECAW/WS20	23.00	$2,208.00	01 / 03 / 2001
				$4,266.00	
54	JD HARDWOODS				
		ADMIRAL/WS16	49.00	$2,646.00	01 / 03 / 2001
		AG145/QT01	40.00	$720.00	01 / 03 / 2001
				$3,366.00	
55	WETSEL INC				
		ADMIRAL/GL04	48.00	$2,640.00	01 / 03 / 2001
		AG145/GL04	35.00	$1,470.00	01 / 03 / 2001
		AG36/D055	8.00	$2,776.00	01 / 03 / 2001
				$6,886.00	
56	EXTERIOR DESIGNS				
		ADMIRAL/D030	5.00	$1,915.00	01 / 03 / 2001
		AVO1090/D030	5.00	$2,395.00	01 / 03 / 2001
		BASOILBLUE25/D005	5.00	$4,415.00	01 / 03 / 2001
				$8,725.00	
57	SAN JOAQUIN HELICOPTERS				
		ADMIRAL/D030	11.00	$4,213.00	01 / 03 / 2001
		AG36/G202	19.00	$1,178.00	01 / 03 / 2001
		BIOGAIN/JR12	28.00	$2,940.00	01 / 03 / 2001
				$8,331.00	
58	PALEX TEXAS L.P.				
		ADMIRAL/D030	7.00	$2,681.00	01 / 03 / 2001
				$2,681.00	
59	Bellmawr Ecological Center				
		ADMIRAL/T275	1.00	$3,243.00	01 / 03 / 2001
				$3,243.00	

Printed Date: 10/23/2002

Report No.003 Customer Order Sorted by Sales Order Numbers

SO. No.	Customer Name	Product Name	Order Qty.	Amount	Promised Date
60	TERRE CO THE				
		BASOILBLUE25/D005	4.00	$3,532.00	01 / 04 / 2001
		BIOGAINFECA/WS20	33.00	$2,310.00	01 / 04 / 2001
				$5,842.00	
61	MIDLAND IRON & STEEL				
		ADMIRAL/GL04	46.00	$2,530.00	01 / 04 / 2001
				$2,530.00	
62	SAN JOAQUIN HELICOPTERS				
		AVO1090/D030	5.00	$2,395.00	01 / 04 / 2001
		BIOGAINFECA/WS20	18.00	$1,260.00	01 / 04 / 2001
				$3,655.00	
63	ENVIRONMENTAL SIGHT DEVELOP				
		AB9/D030	4.00	$2,944.00	01 / 04 / 2001
		AG36/QT12	31.00	$2,418.00	01 / 04 / 2001
		BASOILRED/PT12	15.00	$1,470.00	01 / 04 / 2001
				$6,832.00	
64	TARGET SPECIALTY PRODUCTS				
		AG145/GL04	52.00	$2,184.00	01 / 04 / 2001
		AG145/GL06	8.00	$496.00	01 / 04 / 2001
		BIOGAIN/JR12	23.00	$2,415.00	01 / 04 / 2001
				$5,095.00	
65	TWOMBLY NURSERY INC.				
		ADMIRAL/WS16	39.00	$2,106.00	01 / 04 / 2001
		AG145/GL04	41.00	$1,722.00	01 / 04 / 2001
		AVO1090/D030	5.00	$2,395.00	01 / 04 / 2001
				$6,223.00	
66	HELDERBURG MOUNTAIN MULCH (				
		AG145/D055	8.00	$2,776.00	01 / 04 / 2001
		AG36/G202	28.00	$1,736.00	01 / 04 / 2001
		BIOGAINFECAW/WS20	24.00	$2,304.00	01 / 04 / 2001

Printed Date: 10/23/2002

Report No.003 **Customer Order Sorted by Sales Order Numbers**

SO. No.	Customer Name	Product Name	Order Qty.	Amount	Promised Date
				$6,816.00	
67	SOUTHERN MILL CREEK PRODUCT				
		BIOGAINFE/WS20	35.00	$2,485.00	01 / 04 / 2001
				$2,485.00	
68	CAMCO				
		ADMIRAL/D030	2.00	$766.00	01 / 04 / 2001
		AG145/G202	43.00	$2,666.00	01 / 04 / 2001
		BASOILBLUE25/D005	4.00	$3,532.00	01 / 04 / 2001
				$6,964.00	
69	RYAN OIL COMPANY INC				
		AG145/G202	46.00	$2,852.00	01 / 04 / 2001
		AG36/G202	31.00	$1,922.00	01 / 04 / 2001
		AG36/QT01	84.00	$672.00	01 / 04 / 2001
				$5,446.00	
70	FULLER PETROLEUM COMPANY				
		AG36/QT12	27.00	$2,106.00	01 / 04 / 2001
				$2,106.00	
71	Bueshing Peat Moss				
		BIOGAIN/JR12	22.00	$2,310.00	01 / 05 / 2001
				$2,310.00	
72	NATIONAL LIQUID FERTILIZER				
		AB9/D030	2.00	$1,472.00	01 / 05 / 2001
		BASOILBLUE/GL04	17.00	$1,683.00	01 / 05 / 2001
		BIOGAINFE/WS20	13.00	$923.00	01 / 05 / 2001
				$4,078.00	
73	ADVANCED BIOLOGICAL SOLUTI				
		BIOGAINFE/WS20	37.00	$2,627.00	01 / 05 / 2001

Printed Date: 10/23/2002

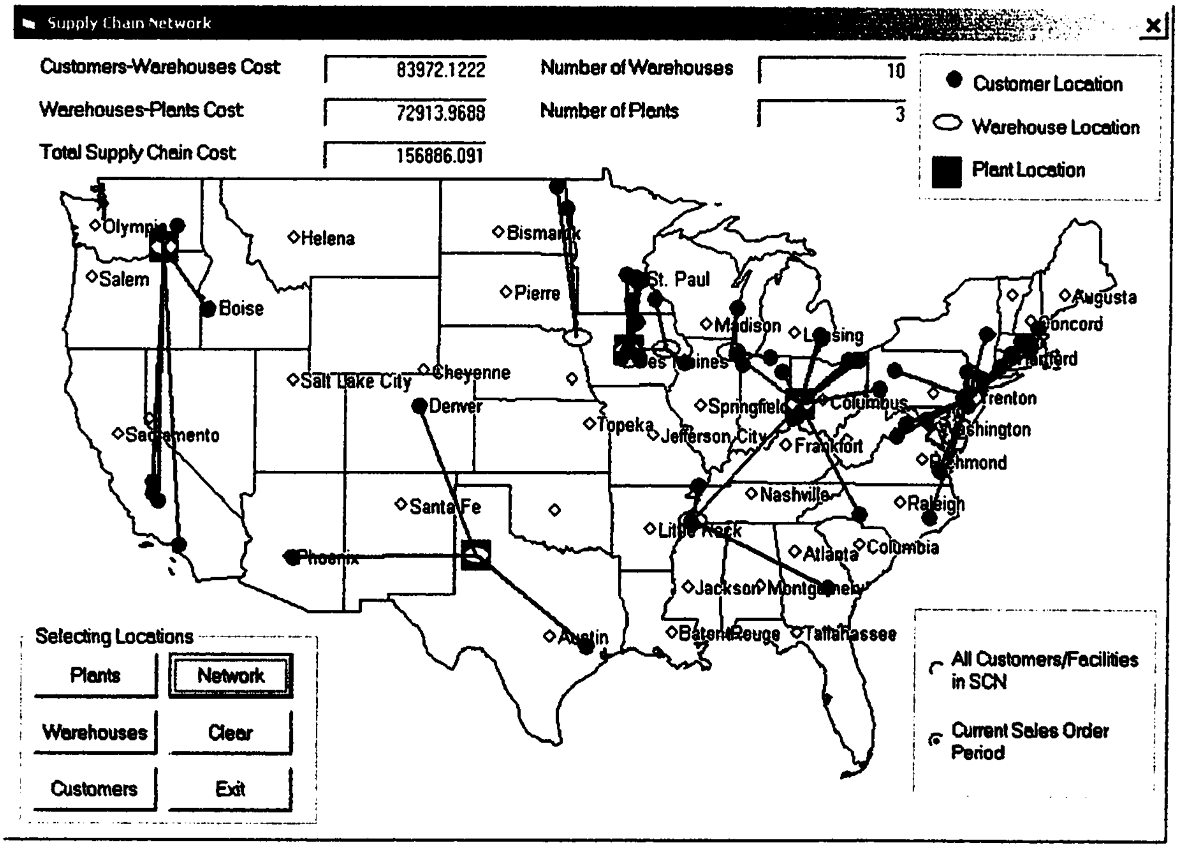
Report No.003 Customer Order Sorted by Sales Order Numbers

SO. No.	Customer Name	Product Name	Order Qty.	Amount	Promised Date
				$2,627.00	
74	CAMCO				
		AG36/G202	31.00	$1,922.00	01 / 05 / 2001
		AG36/GL04	46.00	$1,794.00	01 / 05 / 2001
		BIOGAINFE/WS20	30.00	$2,130.00	01 / 05 / 2001
				$5,846.00	
75	VIRGINIA GROUND COVERS				
		AG145/GL06	14.00	$868.00	01 / 05 / 2001
		BIOGAINFE/WS20	37.00	$2,627.00	01 / 05 / 2001
				$3,495.00	
76	QUABBIN LUMBER				
		BIOGAINFECAW/WS20	40.00	$3,840.00	01 / 05 / 2001
				$3,840.00	
77	PRECISION TURF AND CHEMICAL				
		AG145/QT12	19.00	$1,596.00	01 / 05 / 2001
		AVO1090/D030	3.00	$1,437.00	01 / 05 / 2001
		BASOILBLUE25/D005	2.00	$1,766.00	01 / 05 / 2001
				$4,799.00	
78	JACKSON INDUSTRIAL PROCESSIN				
		AG36/GL04	59.00	$2,301.00	01 / 05 / 2001
				$2,301.00	
80	HUNGERFORD BROS				
		BIOGAINFECAW/WS20	24.00	$2,304.00	01 / 05 / 2001
				$2,304.00	
81	FECON INC.				
		AVO1090/D030	9.00	$4,311.00	01 / 05 / 2001
				$4,311.00	

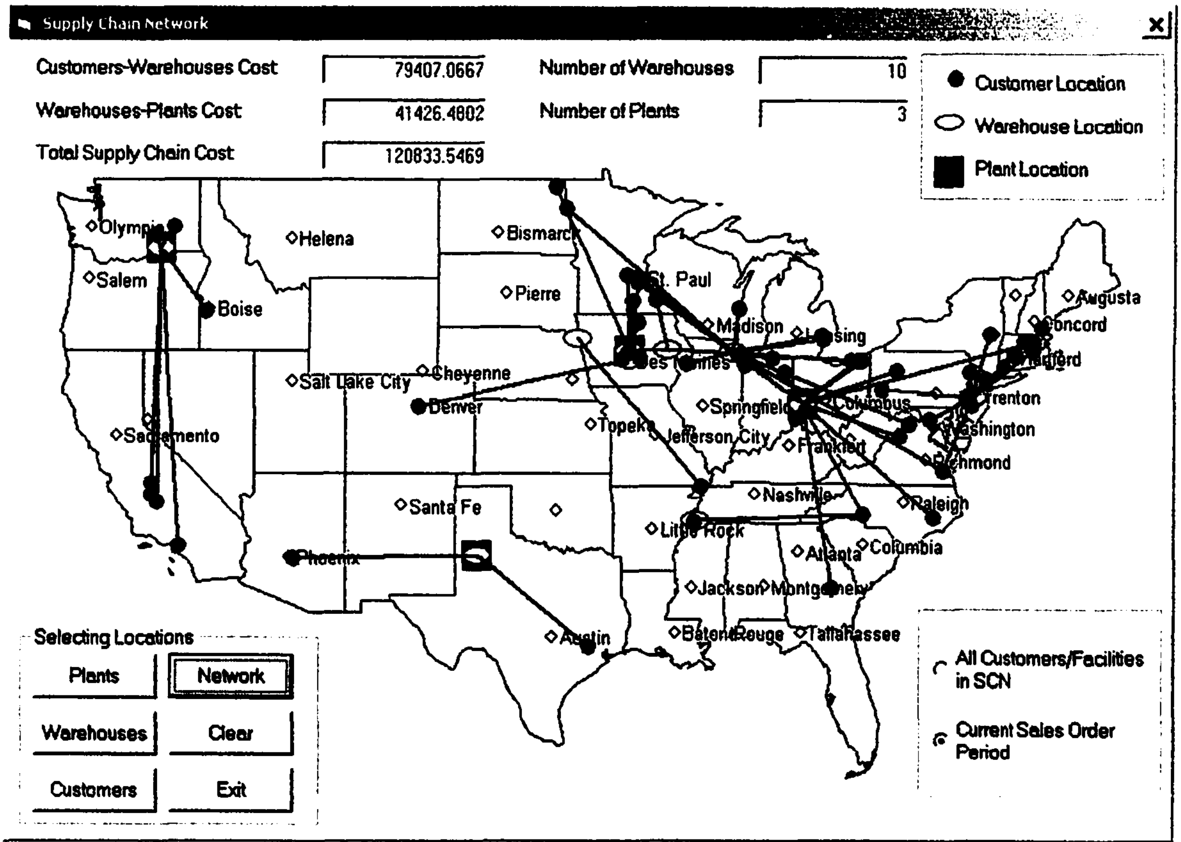
Printed Date: 10/23/2002

APPENDIX B
EXAMPLE RESULTS OF SUPPLY CHAIN NETWORK

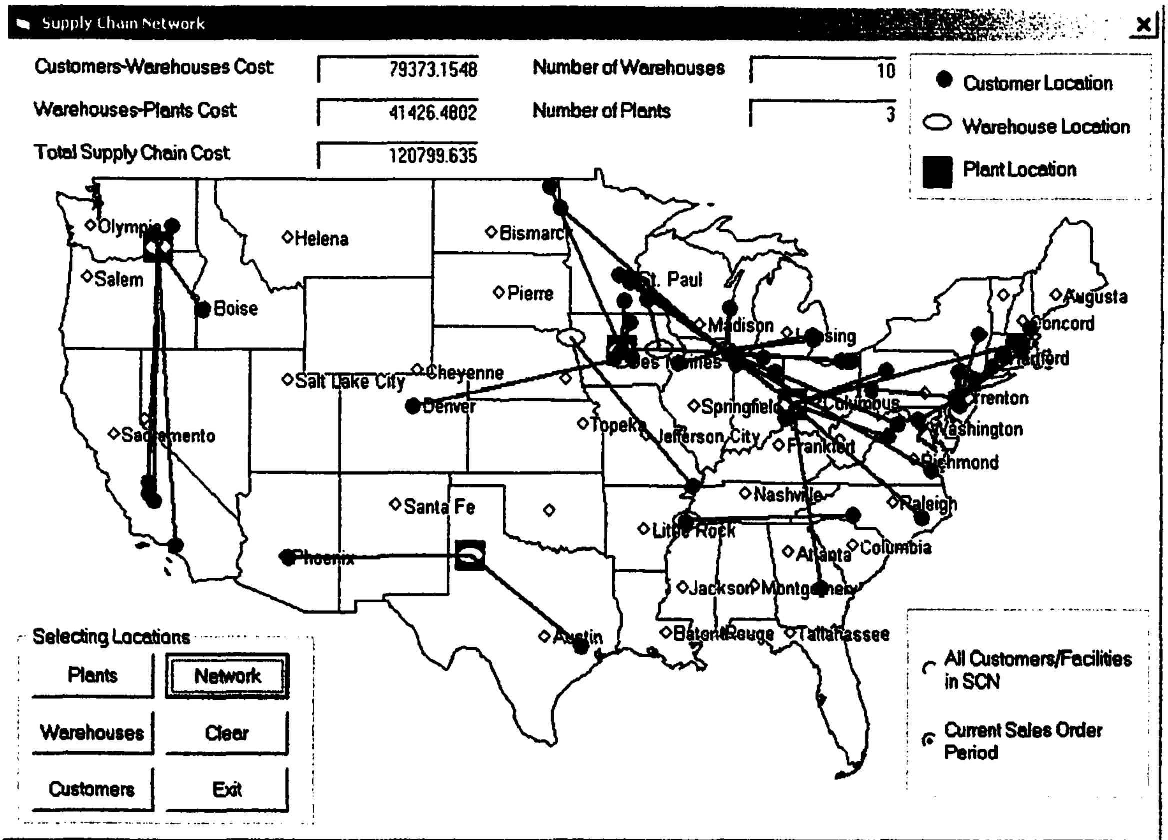
Supply Chain Network using the Shortest Distance Method



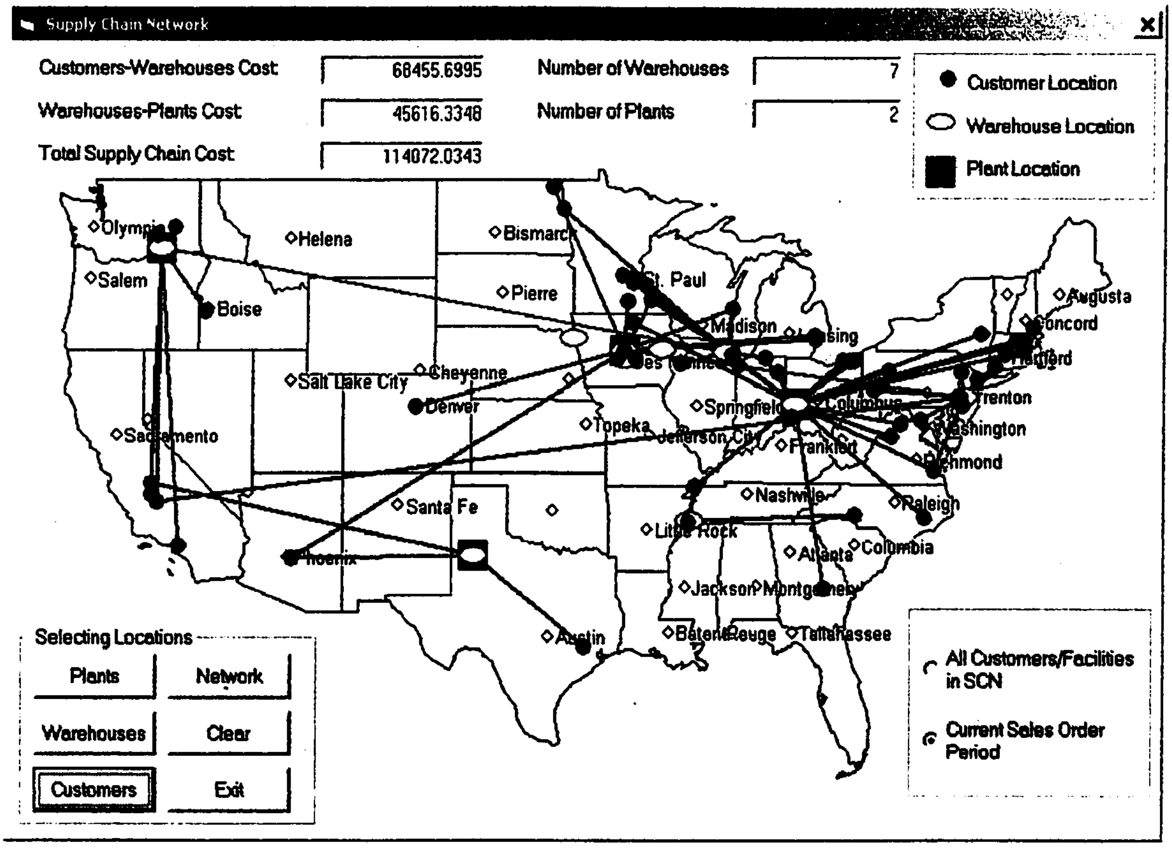
Supply Chain Network using the Lowest Transportation Cost Method



Supply Chain Network using the Single Warehouse Preference Method



Supply Chain Network using PSCMP Heuristic Method



APPENDIX C
EXAMPLE RESULTS OF A PULL-BASED SUPPLY CHAIN DECISIONS FROM THIS STUDY

Report No.005

Shipping Information Sorted by Customer Names

Customer Name	ProductName	SO.No	Order Qty	Amount	Promised Date	Shipping Warehouse	Shipping Qty
A & L SUPPLY							
	BIOGAINFE/WS20	19	21	$1,491.00	1/1/2001	INLAND EMPIRE	21
	ADMIRAL/WS16	19	6	$324.00	1/1/2001	INLAND EMPIRE	6
ADVANCED BIOLOGICAL SOLUTIONS							
	BIOGAINFE/WS20	73	37	$2,627.00	1/5/2001	BECKER UNDERWOOD	37
AMERICAN CLAY WORKS AND SUPPLY CO							
	AVO1090/D030	52	3	$1,437.00	1/3/2001	BECKER UNDERWOOD	3
	AG145/D055	52	3	$1,041.00	1/3/2001	BECKER UNDERWOOD	3
ARBORCHEM PRODUCTS CO							
	AVO1090/D030	42	9	$4,311.00	1/2/2001	JACOBSON WAREHOUSE CO	9
	AG36/D055	42	5	$1,735.00	1/2/2001	JACOBSON WAREHOUSE CO	5
	BASOILBLUE25/D005	42	5	$4,415.00	1/2/2001	JACOBSON WAREHOUSE CO	5
ARTISAN LANDSCAPING							
	BASOILBLUE25/D005	34	4	$3,532.00	1/1/2001	GRANTEC	4
Bellmawr Ecological Center							
	ADMIRAL/T275	59	1	$3,243.00	1/3/2001	JACOBSON WAREHOUSE CO	1
BEST SAND CORPORATION							
	AG36/GL04	45	34	$1,326.00	1/2/2001	GRANTEC	34

Printed Date: 10/23/2002

Report No.006

Shipping Information Sorted by Promised Date

Promised Date	Customer Name	Product Name	SO. No.	Order Qty	Amount	Shipping Warehouse	Shipping Qty.
1/1/2001							
	A & L SUPPLY						
		BIOGAINFE/WS20	19	21	$1,491.00	INLAND EMPIRE	21
		ADMIRAL/WS16	19	6	$324.00	INLAND EMPIRE	6
	ARTISAN LANDSCAPING						
		BASOILBLUE25/D005	34	4	$3,532.00	GRANTEC	4
	CHEM TECH						
		AG36/GL04	25	68	$2,652.00	BECKER UNDERWOOD	68
		ADMIRAL/D030	25	7	$2,681.00	ROBERTSON	7
		BIOGAIN/WS40	25	17	$901.00	ROBERTSON	17
	F & G REALTY						
		ADMIRAL/D030	31	8	$3,064.00	JACOBSON WAREHOUSE CO. (PA)	8
		ADMIRAL/GL04	31	97	$5,335.00	JACOBSON WAREHOUSE CO. (PA)	97
	INTERNATIONAL RESOURCE GROUP						
		BIOGAINCA/WS40	30	44	$2,376.00	ROBERTSON	44
	M.D. PRICE						
		AG36/GL04	23	75	$2,925.00	GRANTEC	75

Printed Date: 10/23/2002

Report No.007

Shipping Information Sorted by Sales Order Numbers

SO.No.	Customer Name	Product Name	Order Qty.	Amount	Promised Date	Shipping Warehouse	Shipping Qty.
19	A & L SUPPLY						
		BIOGAINFE/WS20	21	$1,491.00	1/1/2001	INLAND EMPIRE	21
		ADMIRAL/WS16	6	$324.00	1/1/2001	INLAND EMPIRE	6
20	SEED BIOTICS						
		AG36/GL04	72	$2,808.00	1/1/2001	INLAND EMPIRE	72
		AG36/D055	3	$1,041.00	1/1/2001	INLAND EMPIRE	3
		ADMIRALW/WS16	38	$2,204.00	1/1/2001	INLAND EMPIRE	38
21	WILBUR ELLIS						
		AG145/GL04	14	$588.00	1/1/2001	STERLING QUALITY LOGISTICS	14
		BIOGAINFECAW/WS20	18	$1,728.00	1/1/2001	STERLING QUALITY LOGISTICS	18
22	TURF SUPPLY COMPANY						
		BIOGAINFE/WS20	10	$710.00	1/1/2001	GRANTEC	10
		AG145/QT01	96	$1,728.00	1/1/2001	GRANTEC	96
		BIOGAIN/JR12	19	$1,995.00	1/1/2001	GRANTEC	19
23	M.D. PRICE						
		AG36/GL04	75	$2,925.00	1/1/2001	GRANTEC	75

Printed Date: 10/23/2002

Report No.008

Shipping Information Sorted by Product Names

Product Name	CompanyName	SO. No.	Order Qty	Promised Date	Amount	Shipping Warehouse	Shipping Qty
AB9/D030							
	ENVIRONMENTAL SIGHT DEVELOP	63	4	1/4/2001	$2,944.00	JACOBSON WAREHOUSE CO. (PA)	4
	NATIONAL LIQUID FERTILIZER	72	2	1/5/2001	$1,472.00	STERLING QUALITY LOGISTICS	2
ADMIRAL/D030							
	PALEX TEXAS L.P.	58	7	1/3/2001	$2,681.00	NICKEY WAREHOUSE, INC.	7
	POCONO TURF SUPPLY CO INC	35	9	1/1/2001	$3,447.00	JACOBSON WAREHOUSE CO. (PA)	9
	MIDDLE SMITHFIELD MATERIALS	24	2	1/1/2001	$766.00	JACOBSON WAREHOUSE CO. (PA)	2
	CHEM TECH	25	7	1/1/2001	$2,681.00	ROBERTSON	7
	EXTERIOR DESIGNS	56	5	1/3/2001	$1,915.00	GRANTEC	5
	E.H. GRIFFITH INC	51	3	1/2/2001	$1,149.00	JACOBSON WAREHOUSE CO. (PA)	3
	KIMBALL TREE SERVICE	36	7	1/2/2001	$2,681.00	JACOBSON WAREHOUSE CO. (PA)	7
	F & G REALTY	31	8	1/1/2001	$3,064.00	JACOBSON WAREHOUSE CO. (PA)	8
	SAN JOAQUIN HELICOPTERS	57	11	1/3/2001	$4,213.00	JACOBSON WAREHOUSE CO. (PA)	11
	CAMCO	68	2	1/4/2001	$766.00	ROBERTSON	2

Printed Date: 10/23/2002

Report No.009

Shipping Information Sorted by Warehouse Name

Shipping Warehouse	Customer Name	SO. No,	ProductName	Order Qty	Amount	Promised Date	Shipping Qty
BECKER UNDERWOOD							
	ADVANCED BIOLOGICAL SOLUTIONS						
		73	BIOGAINFE/WS20	37	$2,627.00	1/5/2001	37
	AMERICAN CLAY WORKS AND SUPPLY CO						
		52	AVO1090/D030	3	$1,437.00	1/3/2001	3
		52	AG145/D055	3	$1,041.00	1/3/2001	3
	BJORNSON OIL COMPANY						
		41	BIOGAINFE/WS20	37	$2,627.00	1/2/2001	37
	BOSS SUPPLY INC						
		46	AG145/D055	9	$3,123.00	1/2/2001	9
	CHEM TECH						
		25	AG36/GL04	68	$2,652.00	1/1/2001	68

Printed Date: 10/23/2002

Report No.010

Inventory Replenishment Sorted by Warehouse Names

Warehouse Name	Product Name		Replenishment Qty	From Plant Name
INLAND EMPIRE				
	AG36/D055			
	AG36/D055		51.00	Inland Empire
		Grand Total	**51.00**	
JACOBSON WAREHOUSE CO. (PA)				
	ADMIRAL/D030			
	ADMIRAL/D030		40.00	Becker Underwood
		Grand Total	**40.00**	
STERLING QUALITY LOGISTICS				
	AG36/D055			
	AG36/D055		32.00	Inland Empire
		Grand Total	**32.00**	

Printed Date: 10/23/2002

Report No.011

Inventory Replenishment Sorted by Product Names

Product Name	Warehouse Name	Replenishment Qty	From Plant Name
ADMIRAL/D030			
	JACOBSON WAREHOUSE CO. (PA)		
	JACOBSON WAREHOUSE CO. (PA)	40.00	Becker Underwood
	Grand Total	**40.00**	
AG36/D055			
	INLAND EMPIRE		
	INLAND EMPIRE	51.00	Inland Empire
	STERLING QUALITY LOGISTICS		
	STERLING QUALITY LOGISTICS	32.00	Inland Empire
	Grand Total	**83.00**	

Printed Date: 10/23/2002

Report No.012

Inventory Replenishment Sorted by Plant Names

From Plant Name	To Warehouse Name	Product Name	Replenishment Qty
Becker Underwood			
	JACOBSON WAREHOUSE CO. (PA)		
		ADMIRAL/D030	40.00
Inland Empire			
	INLAND EMPIRE		
		AG36/D055	51.00
	STERLING QUALITY LOGISTICS		
		AG36/D055	32.00

Printed Date: 10/23/2002

Report No.013

Production Plan Summary Report

Product Name	Becker Underwood	Inland Empire	Total
ADMIRAL/D030	40.00	0.00	40.00
AG36/D055	0.00	83.00	83.00

Printed Date: 10/23/2002

Report No.014 **Production Plan Sorted by Plant Names**

PlantName	ProductName	NumberofUnits
Becker Underwood		
	ADMIRAL/D030	40.00
Inland Empire		
	AG36/D055	51.00
	AG36/D055	32.00

Printed Date: 10/23/2002

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BIOGRAPHICAL SKETCH

Pongchai Athikomrattanakul was born in Bangkok, Thailand. He attended King Mongkut's University of Technology Thonburi in Bangkok, Thailand where he received the Bachelor of Science with the first class honor in 1993. He was awarded the Royal Thai Scholarship in 1996 to pursue graduate studies at Iowa State University of Science and Technology in Ames, Iowa where he received the Master of Science in Industrial Engineering in 1998. He has served as a Research Assistant and Teaching Assistant in the Department of Industrial and Manufacturing Systems Engineering at Iowa State University. He was awarded Graduate College Scholarship in 2001 and received the Graduate Teaching Excellent Award in August 2002. He was also nominated as an outstanding teaching assistant at Iowa State University in 2000 and 2002.