MULTI ITEM INTEGRATED LOCATION/INVENTORY PROBLEM

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
THE MIDDLE EAST TECHNICAL UNIVERSITY

BY

BURCU BALÇIK

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE
OF
MASTER OF SCIENCE
IN
THE DEPARTMENT OF INDUSTRIAL ENGINEERING

AUGUST 2003

Approval of the Graduate School of Natural and Applied Sciences

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ABSTRACT

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August 2003, 187 pages

In this study, the design of a three-level distribution system is considered in which a single supplier ships a number of items to the retailers via a set of distribution centers (DC) and stochastic demand is observed at the retailers. The problem is to specify the number and location of the DCs, and the assignment of the retailers to the DCs in such a way that total facility, transportation, safety stock, and joint ordering and average inventory costs are minimized, and customer service requirements are satisfied. Single source constraints are imposed on the assignment of the retailers to the DCs. The integrated location/inventory model incorporates the inventory management decisions into the strategic location/allocation decisions by considering the benefits of risk pooling and the savings that result in the joint replenishment of a group of items. We develop two heuristic methods to solve the non-linear integer-programming model in an integrated way: (1) Improvement type heuristic, (2) Constructive type heuristic. The heuristic algorithms are tested on a number of problem instances with 81 demand points (retailers) and 4 different types of items. Both of the heuristics are able to generate solutions in very reasonable times. The results are compared to the results of the p-median problem and found that the total cost and the number of DCs can be lowered using our integrated model instead of the p-median problem. Finally, sensitivity analysis is performed with respect to the changes in inventory, transportation, and ordering cost parameters, and variability of the demand.

Keywords: Constructive Type Heuristics, Distribution System Design, Facility Location Problem, Improvement Type Heuristics, Integrated Location/Inventory Problem, Joint Replenishment Policies, P-median Problem, Risk Pooling, Supply Chain Management

ÖZ

ÇOK ÜRÜNLÜ TÜMLEŞİK YER BELİRLEME/ENVANTER PROBLEMİ

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Ağustos 2003, 187 sayfa

Bu çalışmada, tek tedarikçinin birden fazla ürünü dağıtım merkezleri yoluyla perakendecilere gönderdiği üç seviyeli bir dağıtım sisteminin tasarımı ele alınmıştır. Bayilerde belirsiz talep gözlenmektedir. Problem; toplam tesis, taşıma, emniyet stoğu ve ortak sipariş ve ortalama envanter maliyetlerini en küçültecek ve müşteri hizmet gereklerini karşılayacak şekilde dağıtım merkezlerinin sayısının ve yerlerinin belirlenmesi ile perakendecilerin dağıtım merkezlerine atanmasıdır. Tümleşik yer belirleme/envanter modeli; stratejik yer belirleme/tahsis etme kararlarına risk ortaklaması faydalarını ve ürünlerin gruplar halinde sipariş edilmesinden doğan kazançları dikkate alarak envanter yönetimi kararlarını dahil etmektedir. Doğrusal olmayan tamsayı programlama modelini tümleşik olarak çözebilmek için iki sezgisel yöntem geliştirilmiştir: (1) Geliştirici tip sezgisel yöntem, (2) Yapıcı tip sezgisel yöntem. Sezgisel yöntemler 81 talep noktası (perakendeci) ve 4 farklı ürün çeşidi olan çok sayıda problem örneği için denenmiştir. Her iki sezgisel yöntem de çok

karşılaştırıldığında, *p*-medyan modeli yerine tümleşik model kullanılarak toplam maliyetin ve dağıtım istasyonu sayısının düşürülebileceği bulunmuştur. Son olarak envanter, taşıma ve sipariş maliyeti parametrelerindeki değişiklikler ve talep değişkenliği üzerine duyarlılık analizi yapılmıştır.

Anahtar Kelimeler: Yapıcı Tip Sezgisel Yöntemler, Dağıtım Sistemi Tasarımı, Tesis Yer Belirleme Problemi, Geliştirici Tip Sezgisel Yöntemler, Tümleşik Yer Belirleme/Envanter Problemi, Ortak Sipariş Politikaları, P-medyan Problemi, Risk Ortaklaması, Tedarik Zinciri Yönetimi

DEDICATION

To my family…

ACKNOWLEDGMENTS

First of all, I would like to thank to my supervisor, Assist. Prof. Dr. Sedef Meral, for her instructive guidance, insight, and endless support during this study. She has welcomed my questions and problems with a high spirit and patience all the time. This study would never be completed without our continuous discussions, and her valuable advice and comments.

I should express my gratefulness to Murat, for being nearby all the time with his continuous support, encouragement and willingness to help. Life would be unbearable without his sense of humor reminding me not to take everything too seriously.

I owe thanks to Deniz for her support, help and friendship. I hope to have a chance to work with her in the future. I thank to Erdem, my office-mate, for his understanding and his efforts to cheer me up when I was bored. I also thank to all my friends in the department for their support and ever smiling faces.

I thank to my parents for their support and encouragement at every stage of my education. Thanks to my brother, Burak, for being an understanding and patient housemate.

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CHAPTER 1

INTRODUCTION

A supply chain can be described as a network of facilities and distribution options that performs the functions of materials procurement, transformation of the materials into intermediate and finished products, and product distribution to customers. Supply chains exist in both service and manufacturing organizations and the complexity of the chain may vary greatly from industry to industry and firm to firm (Ganeshan, Harrison, 1995). The goal of supply chain management is to optimize the entire system, which consists of different functions with conflicting objectives (Simchi-Levi, Kaminsky, Simchi-Levi, 2000). For years, researchers and practitioners have primarily investigated the various processes of the supply chain individually. Recently, however, there has been increasing attention placed on the performance, design, and analysis of the supply chain as a whole (Beamon, 1998).

Supply chain models integrate different functions of the supply chain and allow the consideration of the trade-off between these functions within the supply chain. Effective integration of these various functional entities is the primary objective of supply chain planning. In other words, effective management of a supply chain must take into account the coordination of all of the functions of the chain without degrading the quality or customer satisfaction, while still keeping costs down. Reduced inventories, lower operating costs, and customer satisfaction are some of the benefits, which can be achieved by effective supply chain management.

The decisions associated with supply chain management cover both the long-term and short-term decisions. According to the time horizon of the decisions, they can be classified as strategic, tactical and operational decisions. Strategic decisions deal with corporate policies, which consider the overall design and the structure of the supply chain, and require high capital investment. Typically, strategic decisions are not reviewed before a time horizon of a few to several years expires. Tactical decisions concern the annual or seasonal adjustments of the organization's operations and require moderate capital investment. Operational decisions are short-term decisions, which focus on the everyday activities and problems of an organization's supply chain and involve relatively low level of investment.

Traditionally, the decisions concerning different time horizons have been optimized sequentially, in the sense that the optimized output of one stage becomes the input to the following stage. In other words, tactical and operational level decisions are optimized assuming strategic-level decisions are already made. However, the effectiveness of a supply chain is affected by the interaction among all decisions made at different levels. Therefore, an organization must structure its supply chain through long-term analysis, focusing on its medium-term and short-term activities simultaneously. Substantial savings have been achieved by the companies that applied an integrated analysis to their operations. Some of these cases are presented by Blumenfeld et al. (1987), Robinson, Gao and Muggenborg (1993), and Sery, Presti and Shobrys (2001). The problem of simultaneously considering the characteristics and requirements of different functions to perform an overall optimization has attracted the attention of researchers during the recent years; as a result, some analytical models have been proposed in this direction. The objective of this thesis is to develop a model that provides such an integrated view, considering the decisions related to the distribution stage of the supply chain.

From an overall perspective, a supply chain network can be analyzed in three stages, which are the supplier stage, the plant stage and the distribution stage (Erengüç, Simpson, Vakharia, 1999). The distribution stage decisions can be classified broadly as distribution network, location/allocation and inventory decisions. Briefly, the distribution network decisions are strategic-level decisions that consider the type of the network configuration of the distribution channel. These types of decisions are related to the centralization or decentralization of the distribution network and the determination of the distribution strategies that are to be utilized. Location/allocation decisions are also regarded as strategic level decisions that are mainly about the selection of distribution center (DC) sites and the allocation of service zones to the selected DC sites. Location decisions reflect a company's basic strategy for building and delivering its products to the market. Allocation decisions determine the cost of supplying the customers from the DC sites, which is a function of which DC sites are chosen. Due to the interrelationship between the location decisions and allocation decisions, it would be preferable to adopt an approach for the simultaneous determination of location and allocation decisions. Lastly, the inventory decisions are considered as tactical/operational level decisions and they are mainly related to planning and control of inventory to be maintained at each potential stocking location. In this study, we assume that the type of the distribution network and distribution strategy is predetermined as having an intermediary (distribution centers) between the suppliers and customers. The distribution centers keep inventory and provide customers with items as required. Therefore, we focus only on the location/allocation and inventory decisions at the distribution stage of the supply chain.

Location decisions have strong impacts on the cost and performance characteristics of a supply chain. Determination of the locations of manufacturing and warehousing facilities has received considerable attention from academicians over the past four decades. Location models have been formulated to answer the questions as: how many facilities to establish, where to locate them, and how to distribute the products to the customers in order to satisfy demand and minimize total cost. It is observed that traditional location models seek optimal solutions by considering only the transportation and facility costs but ignoring the inventory costs. Most location models do not explicitly incorporate inventory; rather they consider the flow of products through the system and charge throughput costs for the amount of products that flow through the warehouses. This fails to recognize the interdependence between location and inventory decisions and misrepresents inventory costs in location models (Daskin, 1985). However, one of the most important aspects that affect the performance of a given supply chain is the management of inventories, since the decisions taken in this respect have a significant impact on service levels and total cost in the supply chain. Moreover, the cost and service level performance of a distribution system depends heavily on the interaction between the physical design of the distribution system and the inventory control system. The location of distribution centers and the allocation of retailers to the distribution centers have a significant effect on the total inventory investment, inventory distribution, and customer service (Schwarz, 1981).

The location and inventory models are linked because it is crucial to consider, at least approximately, the inventory implications of location decisions at the strategic level, and the decisions about the inventory allocation must be made within the overall system structure determined by the strategic analysis.

In this study, the design of a distribution system is considered in which a single supplier ships a number of items to the retailers. Some of the retailers are set as distribution centers, where some amount of safety stock is maintained to achieve suitable service levels. A retailer, which is chosen as a distribution center, orders the items from the supplier and distributes them to the other retailers. A modification of the (R,S,s) type periodic review policy is assumed to be implemented at the distribution centers for the control of the inventories of the multiple items. The objective of our problem is to specify the number and locations of the distribution centers in such a way that total facility, inventory and transportation costs are minimized and customer service requirements are satisfied. We incorporate inventory management decisions into the strategic location/allocation decisions and model them with an integrated approach. The main difference of our problem from the multi-item distribution system design problems is that, our study considers a multi-item inventory policy followed at the distribution centers and incorporates the inventory related decisions implied by the multi-item inventory policies into the strategic location/allocation decisions. A multi-item inventory system is usually characterized by some interaction among the items. Savings in the ordering cost may result when several items are ordered simultaneously or when several items are replenished from a single supplier. The incentive behind the desire for joint ordering of the items as a group lies in the fact that, if each item is replenished individually, the major ordering cost is associated with for each of these individual replenishments, which does not accurately indicate the situation faced by most firms (Snyder, Daskin, Teo, 2002). To the best of our knowledge, there is no study in the literature that considers the cost implications of a joint replenishment policy while designing a multi-item distribution system.

We formulate a multi-item integrated location/inventory model that considers the facility costs, inbound and outbound transportation costs, safety stock costs and the cost implications of a joint replenishment policy used at the distribution centers. Due to the complexity of the exact analysis of the (R,S,s) type multi-item inventory problem, we approximate the (R,S,s) policy by assuming that the demand is deterministic. Then a lower bound for the cost of best joint replenishment policy is incorporated into the model, which is derived in Silver, Pyke, and Peterson (1998) by using an efficient heuristic to solve the deterministic joint replenishment problem. After formulating the model, the development of a solution algorithm, which would handle the difficulties posed by the nonlinear terms in the objective function and the structural properties of the joint replenishment policy, is required. We then use two heuristic procedures to solve the non-linear integer-programming model with an integrated approach. The improvement type algorithm and the constructive type algorithm developed are based on some traditional heuristic location algorithms. Both of the algorithms are tested on the generated problem instance and they are compared in terms of their solution qualities and computation times. Moreover, the solutions obtained by these algorithms for the integrated inventory/location problem are compared to the solutions of the p-median problem, which only considers local delivery costs in locating facilities. We also perform sensitivity analysis to find how the solutions obtained respond to the changes in the transportation, inventory, and joint ordering cost parameters, and also variability of the demand.

The rest of the study is organized as follows: In the second chapter, the literature about the strategic location/allocation models, the joint replenishment policies, and the related solution methodologies are reviewed. In Chapter 3, the multi-item integrated location/inventory problem is defined, and the way the inventory policies are incorporated into the location/allocation model is explained. The detailed analysis of improvement type and the constructive type algorithms developed to solve the formulated non-linear integer programming model is provided in Chapter 4. In Chapter 5, the problem instances used for the computations are explained, and the computational results are provided. Finally, conclusions and suggestions for future research are elaborated in Chapter 6.

CHAPTER 2

LITERATURE REVIEW

Operations Research has contributed many models and methods for distribution planning since its early years, in particular, for locating warehouses, but also for more comprehensive design problems. The distribution/location family of problems covers formulations, which range in complexity from simple single commodity linear deterministic models to multi-commodity nonlinear stochastic versions. In modeling logistics problems, it is important to represent the dynamic and evolutionary nature of the systems, stochastic and uncertain components including future demands, nonlinear costs, and multiple objectives of a firm or agency, multiple products, fixed costs and capacity constraints (Daskin, 1985).

Distribution/location problems can be classified into different categories based on the properties of the problem addressed. Aikens (1985) classifies distribution/location models according to:

1. Whether the underlying distribution network is capacitated or uncapacitated
2. The number of warehouse echelons, or levels
3. The number of commodities (single or multiple)
4. The underlying cost structure for arcs and/or nodes (linear or nonlinear)
5. Whether the planning horizon is static or dynamic
6. Patterns of demand (e.g. deterministic or stochastic, influence of location, etc)
7. The ability to accommodate side constraints (e.g. single-sourcing)

Although the range of previous work on distribution/location problems is quite extensive, comparatively less attention has been paid to warehouse location problems in which inventory costs are a significant determinant of the warehouse locations. A review by Vidal and Goetschalckx (1997) on the strategic production/distribution models highlights that certainty is generally assumed in the models presented in the literature. Most of the formulations focus on a mixed integer programming representation, in which the demands at a set of specified locations are assumed fixed and known with certainty, and, thus, inventory costs are either neglected or assumed to be unrelated to the distribution center location decisions. The models generally include integer variables for locating plants and/or distribution centers in given locations and allocating customers to the distribution centers, and continuous variables for determining flows of products through the system. This approach fails to recognize the interdependence between location and inventory decisions and misrepresents inventory costs in location models (Daskin 1985). Only some recent papers consider the inventory impacts on the number and location of the warehouses on total distribution costs, although facility location and inventory management are intimately related.

In the following section, we review the studies about the distribution system design problem first. Afterwards, some studies about the solution methods that are used to solve location models are reviewed. Lastly, we go over some studies about the joint replenishment policies.

2.1. Distribution System Design Problems

In this section, some studies that do not consider the inventory policies explicitly in their models are reviewed first. Then those studies in which the inventory costs/policies are a significant determinant of the distribution system are presented.

2.1.1. The Studies without Inventory Considerations

Geoffrion and Graves (1974) deal with a distribution design problem which tries to determine the number and location of intermediate distribution facilities between plants and customers, and the allocation of the customers to the opened facilities, in a multi product environment. The mixed integer linear programming model proposed minimizes the sum of fixed warehouse construction and operating costs, variable throughput costs and the transportation costs from plants through warehouses to customers subject to the constraints related to demand, plant capacity, and distribution center throughput. An effective optimal seeking solution approach based on Benders decomposition is developed. The proposed approach is implemented on a large real life problem. Additionally, various types of computer runs such as sensitivity analysis, and tradeoff analysis are carried out in the study.

Kelly and Khumwala (1982) deal with a special case of warehouse location problem that considers the minimization of total costs where, in addition to the effects of spreading fixed costs, there are opportunities to achieve economies of scale in variable warehousing costs. Without the capacity constraints and nonlinear operating costs, the problem is an uncapacitated warehouse location problem. They use an iterative procedure, which solves a series of conventional transportation problems in order to converge to the optimal system design. The algorithm can be used to solve large problems of the type normally encountered in practice.

Ro and Tcha (1984) deal with a facility location problem in a three-level distribution system to locate both plants and warehouses simultaneously. There is no capacity constraint for plants and warehouses. Commodities are delivered from plants to customers either directly or via warehouses. Some side constraints are imposed on the problem, which represent the adjunct relationship of some warehouses to certain plants such that if a plant is open, its associated warehouses are then required to open, but not vice versa. They propose an efficient branch and bound algorithm using a set of simplifications, which are obtained by exploiting the submodularity of the objective function and the special structure of the side constraint. They present computational results on 15 test problems.

Pooley (1994) carries out a study with a project team, at the fluid division of a large dairy processor Ault Foods Limited. The team develops a strategy for the fluid division facilities by analyzing the opportunities associated with the existing and new production and distribution network. The main cost drivers of the system are customer demand, customer-service requirements, production costs and capacity, depot costs and capacity, production sourcing requirements and transportation costs. They split the overall analysis into manageable subcomponents. The distribution network design part of the problem is solved by using a mixed integer programming model based on the work of Geoffrion and Graves (1974). Also, some sensitivity analyses are performed on some factors such as customer demand, capacity, customer service requirements, and operating costs. The results show that changes in customer demand have the greatest impact on total network costs. However, from a unit cost perspective the model is most sensitive to capacity constraints and customer service requirements. Also, the results of the sensitivity analysis are used to study the interrelationship of different variables. Based on the study, the company has established new production and distribution facilities and closed two supply depots, which resulted in operating savings of more than several millions dollars per year.

Hindi, Basta and Pienkosz (1998) consider a three-stage distribution planning problem where the customers are to be served with different commodities from a number of plants, through a number of distribution centers. The demand of customers for each commodity is known and single sourcing constraints are imposed on the model so that each customer is served by only one distribution center for all commodities. Plants and distribution centers have limited capacities. A mixed integer-programming model is developed to locate the distribution centers by minimizing the fixed cost of opening distribution centers, operating costs for handling commodities at open distribution centers and transportation costs. A branch and bound procedure is used to calculate lower bounds and a descent search algorithm is described to generate upper bounds for the problem. The computational results are provided for six classes of problems. The model is computationally efficient and capable of solving realistically large problems due to the effectiveness of the generation of lower bounds and upper bounds. Moreover, the results show that the number of distribution centers and the number of customers affect the computation time much more significantly than the number of commodities and the plants. Pirkul and Jayaraman (1998) also consider a similar problem and solve it by using a Lagrangian based solution algorithm. The only difference is that the location of the plants is also a decision variable in their problem. They also extend their study to account for the production costs at the plants in Jayaraman and Pirkul (2001).

Tragantalerngsak, Holt and Rönnqvist (2000) consider a three-level facility location problem. The plants and the warehouses have capacity limits. Single-source restrictions are imposed on the assignment of the warehouses to the plants, and on the assignment of the customers to the warehouses. They propose an integer programming model to determine the number and locations of the plants and the warehouses, and the assignments of customers to the warehouses as well as the assignments of the warehouses to the plants. They minimize the establishment costs of facilities and the costs of assigning customers to the located warehouses. The proposed model is NP-hard. Previously, Tragantalerngsak (1997) has developed six different Lagrangian relaxation based heuristics for the same problem, each using the structure of the problem in a different fashion. Using the most promising relaxation with respect to both the average gap and the average computing time of these relaxations, Tragantalerngsak, Holt and Rönnqvist (2000) develop a Lagrangian relaxation-based branch and bound method to solve the problem where branch and bound procedure is performed in three stages. Six sets of test problems, each with 20 problem instances, are constructed to test the performance of the proposed algorithm. According to the results, it is concluded that the algorithm is efficient and requires significantly less computational time than those of a standard LP-based 0-1 integer programming package.

Klose (2000) considers a two-stage capacitated facility location problem to find the location of depots to open from a given set of potential depot sites, and to determine the assignment of customers to the open depots and the product flow from plants to depots. This problem is an extension of the one-level capacitated facility location problem in that it considers the transportation costs between plants and warehouses. The problem is formulated as a linear mixed-integer model and a Lagrangian relax-and-cut approach is used to solve the model. The algorithm is tested on two different sets of test problems. The first set of problems is randomly generated, whilst the Swiss road network data are used to generate the second set of problems. The computational results show that the bounds obtained by the proposed method lie within a range of 0.5% (lower bound) and 0.1% (upper bound) from optimality. It is stated that, in the case of small or easy problems, it can take less time to solve the problem optimally using an LP-based cutting plane approach. However, in the case of large or more difficult problems, the Lagrangean relaxation procedure has provided much better upper bounds (and sometimes also lower bounds) in far less running times than the application of an LP-based approach. A weakness of the approach is the large effort to optimize or reoptimize the Lagrangean dual.

Melkote and Daskin (2001) study a two-level capacitated facility location/network design problem and provide a mixed integer programming formulation and some valid inequalities to strengthen its LP relaxation. The model minimizes the sum of transportation costs, facility establishing costs and cost of constructing the links between the facilities and the demand points subject to flow and capacity constraints. The model is tested on 72 test problems. Solutions guaranteed to be within 10% of optimality have been found for 68 of the 72 problems, and solutions within 5% of optimality have been found for 43 problems. Also, some sensitivity analyses are conducted on a particular test problem to gain further insight into the behavior of the model. Particularly, the behavior of total cost and individual cost terms is analyzed with respect to capacity.

2.1.2. The Studies Incorporating Inventory Costs/Policies into the Location Models

Robinson, Gao and Muggenborg (1993) develop an optimization-based decision support system for designing a multi-product distribution system and apply it to a problem facing DowBrands, Inc., which is a manufacturer of food-care products. The existing distribution system of DowBrands consists of four levels, which are plants, central distribution centers (CDCs), and regional distribution centers (RDCs) and customers. Product mixing operations are performed at CDCs, which maintain cycle stock, seasonal stock and safety stock. RDCs maintain cycle stock, safety stock and a minimal amount of seasonal stock. They find out whether a four-level or a three-level system is preferable, determine the number and location of facilities at each level, the assignment of customer demand to facilities, and shipment sizes and routings by product through the distribution system. Warehousing costs are composed of handling costs (per unit) and storage costs (per unit per unit time) and they vary by location. They assume that the facilities are uncapacitated and allow the model determine what the facility capacities should be at each location. A fixed charge network-programming model is used to model the problem and a mathematically equivalent mixed integer programming formulation of this network model is presented. They solve the problem using a dual-based optimization procedure. The problem they consider include 13 CDC, 23 RDC locations with 93 market zones with 3 demand classes in each zone. They evaluate over 60 different cost and customer-service scenarios during the study. Sensitivity analysis is performed particularly to investigate the potential impact of errors in the estimation of facility-fixed cost structures. Also, relationship between the system cost and customer service, which is defined by maximum shipment distance for less-than-truckload deliveries, is analyzed. Finally, they perform what-if analysis by forcing an existing facility that was not recommended in the optimal solutions into the set of opened facilities. Considerable savings are obtained as a result of the study due to the reduction in the number of RDCs.

Barahona and Jensen (1998) describe a two-level logistics design problem that involves the design of a distribution network for computer spare parts. They present an integer programming model to find the location of warehouses and allocate the customers to the warehouses. They include the inventory cost for storing a part in a location. They design networks considering 2-hour, 4-hour and 24-hour service level constraints. Service level constraints are added to the model ensuring that at least a specified percentage of demand is satisfied within a given service level. Also, the single-source constraint added to the model indicates that all spare parts required by a customer should be stored at the warehouse that the customer is assigned to. They use LP relaxation, which can be solved by Dantzig-Wolfe decomposition. The subproblems reduce to the minimum-cut problem. Subgradient optimization is used to accelerate the convergence of Dantzig-Wolfe decomposition. Their solution approach results in near-optimal integer solutions.

Nozick and Turnquist (1998) consider a system consisting of one or more production plants, a set of distribution centers, retail outlets and customers. The number and location of the plants and the retailer outlets is fixed. Individual products having uncertain demands move through the distribution system. It is assumed that expected demand across all retailers is divided equally among the distribution centers. (S-1, S) continuous review policy is implemented where S is order-up-to level. In this inventory policy, retailers order replenishment stock from the distribution centers on a one-for-one basis as products are sold, and the distribution centers in turn order replenishment from the plant(s). Safety stocks of each product are held at the distribution centers to buffer against the uncertain demands at the retailers. The problem is defined as finding the optimal number of distribution centers and their locations by considering fixed facility costs, transportation costs and inventory costs. Their focus is on safety stock in inventory analysis due to the expected square-root relationship between total safety stock and the number of distribution centers (Eppen, 1979). Safety stock requirements are approximated as a linear function of the number of distribution centers and included within fixed-charge coefficient of the fixed-charge facility location model. They use a greedy add-and-improvement heuristic algorithm to solve the fixed-charge facility location model. A distribution system for finished automobiles with 700 vehicle configurations (products) is considered to illustrate the modeling approach. The model recommends 23 regional distribution centers among 698 demand areas. The same authors study on the extensions of this problem by addressing customer responsiveness and maximal coverage and in three more papers. Nozick and Turnquist (2001a) consider the trade-off between customer responsiveness and costs when designing a distribution system by formulating a multi-objective model. By giving a weight to the objective of minimizing uncovered demand in the model, a variety of trade-off solutions are identified. An efficient frontier is obtained by changing the weighting parameter. Solutions with 23 and 64 distribution centers are generated at two extremes with zero and a very large weighting parameter, respectively. In this example, fixed facility costs are less significant in the cost trade-off analysis, since the primary cost trade-offs seem to be between transportation and inventory costs. Nozick (2001b) integrates a maximal covering model within the fixed charge facility location model with a bound. The solution ensures that all demand is served but the uncovered demand will be served at a lower level of service. Two Lagrangian relaxation based heuristics, which are allocation and decoupling, are presented and tested on test networks with 62 and 106 nodes by assuming a coverage distance of 200 miles. Five coverage restrictions changing between 70% and 99% are investigated for each test problem. In the test cases, decoupling heuristic dominates the allocation heuristic in terms of the quality of upper bounds and lower bounds and also in terms of solution times. Finally, Nozick and Turnquist (2001c) consider a two-echelon inventory-distribution system. In addition to determining the optimal number and location of distribution centers by incorporating inventory costs in their location model, they decide which products' inventories should be maintained at both the distribution center and the plants, and which ones should be maintained only at the plant. (S-1, S) continuous review policy is implemented at both the plant and distribution centers. In the inventory analysis, they construct an inventory model that minimizes total stockout costs and inventory holding costs to determine optimal stock levels at each echelon for a given product. The optimal inventory policy depends on the number and location of the distribution centers opened. They integrate the inventory analysis and the location analysis by constructing an iterative procedure that can alternate between solving a fixed-charge facility location problem (given an inventory policy), and solving an inventory optimization problem (given the number and the location of distribution centers). They apply this modeling approach for a distribution system for finished automobiles with 698 demand locations and 260 vehicle configurations belonging to 20 unique volume categories, where first volume category involves highest demand configurations and twentieth volume category involves lowest demand configurations. The converged solution is obtained at the fifth iteration, which recommends opening 45 distribution centers and stocking the first four volume categories at both the distribution centers and the plants.

Erlebacher and Meller (2000) develop a strategic model for the location-inventory problem by considering a three-echelon system involving plants, distribution centers and customers. The location and capacity of the plants is fixed and known, and very large number of customer locations is represented continuously. Rectilinear distances are used to measure the distance between plants and distribution center locations, and between distribution center locations and customer locations. Continuous review inventory system is applied at each distribution center and both cycle stock and safety stock are considered as inventory components at the distribution centers. The objective function of the non-linear integer-programming model minimizes the fixed cost of locating distribution centers, inventory costs at distribution centers and total transportation cost. They do not propose a method to solve the model; rather they develop an analytical model based on some simplifying assumptions to reduce the size of the enumeration on N (number of open distribution centers). They also obtain bounds for the value of N and they use these bounds to develop a heuristic for allocating customers to distribution centers. They present a case study example, motivated by their interaction by Frito-Lay Inc., which has a large distribution system with 42 plants, one regional DC, and 325 local distribution centers, with each plant also acting as a regional distribution center. The results of this study are not reported in the paper.

Karabakal, Günal and Ritchie (2000) address the problem of determining new distribution center locations for Volkswagen in USA. In the existing distribution system, the vehicles are shipped to one of five US ports that act like distribution centers. These ports have processing centers that conduct various handling and quality control checks on all vehicles. Then the vehicles are transported to dealers. The main idea of the study is to establish more distribution centers close to metropolitan areas and to test the effects of this on two performance criteria, which are customer responsiveness and system cost. Customer service is measured by the counts of first and second choice hits at dealers and distributions centers, direct factory orders and lost customers. System cost is the sum of distribution costs and inventory holding costs. Distribution cost occurs during the transportation of vehicles from plant to processing centers, from processing centers to distribution centers and finally from distribution centers to market areas. Inventory holding cost is composed of market inventory, distribution-center inventory, processing center delay, and transportation delay. Two types of facilities are considered for installing at the distribution center locations. They use an iterative method between a mixed integer programming model and a simulation model to obtain the final location policy. Mixed integer programming model is used to generate a reasonable amount of location scenarios by minimizing the distribution and fixed costs. The dynamic and stochastic aspects of the problem are reflected in the simulation model. They state that they reach the final location policy between the mixed integer programming and the simulation in two to three iterations. The results show that adding more than six new distribution centers to the existing ones is not profitable. Volkswagen has opened a number of pilot distribution centers to test the implementation of the findings and realized varying degrees of success.

Daskin, Coullard and Shen (2003) consider expected inventory costs when making facility location decisions via their model that combines strategic and tactical decisions. They address an integrated facility location/inventory location problem by considering a distribution system involving a single supplier and a set of retailers, each with uncertain and independent demand. Some safety stock is maintained at each retailer to achieve acceptable service levels. The small amount of inventory maintained at the retailers is ignored and the inventory policy applied at the distribution centers is based on the EOQ model. The problem is to choose the set of retailers that will serve as distribution centers and become inventory storage locations for other retailers thereby achieving riskpooling benefits and to allocate the other retailers to these distribution centers. Two different mathematical programming models are presented for this problem: a location/allocation model and a set-covering model The location/allocation model includes nonlinear terms in the objective function due to the shipment and inventory costs. To solve the set-covering model, a solution approach using column generation method is developed. Nonlinearity appears in the pricing problem of the set-covering model. 47 problems using 4 different data sets ranging in size from 33 nodes to 150 nodes are generated to test the modelling approach. It is observed that as the inventory holding cost factor gets larger with respect to the distribution cost factor, the problem becomes more difficult to solve. Also, as the transportation costs increase or inventory costs decrease relative to other costs, the number of opened distribution centers increases. Another observation is that the smaller set of opened distribution centers is not necessarily a subset of the bigger set of opened distribution centers. Daskin, Coullard and Shen (2002) developed a Lagrangian based solution algorithm for the location/allocation risk pooling model based on the assumption that the variance-to-mean ratio is assumed to be identical for all retailers. They test their algorithms on problems with 88 and 150 retailers. Also, sensitivity analysis of the results with respect to the changes in transportation and inventory costs is performed. The results are also compared with the traditional uncapacitated fixed charge (UFC) location model and it is found that UFC model locates more distribution centers with lower costs due to the lack of inventory terms in it. When the computational capabilities of the algorithm are compared with the column generation approach that is presented by Daskin, Coullard and Shen (2003), it is found that computation times are consistently lower than those obtained using the column generation approach. However, the computation times with this algorithm grow with larger distribution cost factor, while the computation times with the column generation decrease with large distribution cost factor.

Sery, Presti and Shobrys (2001) consider the BASF North America's distribution system to define the optimal number and location of warehouses and the corresponding material flows needed to meet the anticipated customer demand and the required delivery service times at the lowest overall cost. The distribution system involves three levels, which are plants, distribution centers and demand points. A set of product groups that may require special types of storage requirements flows through the distribution system. Customer service level is measured in terms of the same-day and the next-day deliveries and the cost components are fixed costs for opening distribution centers, variable and handling costs at the distribution centers and freight costs for replenishing distribution centers and shipments to customers. Since both truckload and less-than-truckload shipments exist in the distribution system, network combinations that allow for the use of truckload shipments rather than the more expensive less-than-truckload shipments are identified to reduce the costs. A three-step modeling approach is used to formulate the problem. A single-echelon distribution model is used in the first step of the formulation and the busiest and least active distribution centers, attainable customer service levels, and candidate distribution center locations are obtained. In the second step, they search for the best distribution center candidates by adding constraints that force the model to select between the distribution center locations by adjoining the distribution centers located in the adjacent regions. In the first two steps, the fixed cost of opening distribution centers is not considered in the models, since they take the transportation flow patterns required to serve customer demand as the primary criteria. In the last step, fixed costs and the restrictions on the number of distribution centers to be opened are considered in the model. The alternative configurations are found to outperform the original configuration with 86 distribution centers in terms of both cost and customer service levels. BASF has made changes in its distribution network by opening a new distribution center and eliminating several warehouses, and consolidating storage and handling activities and as a result improved the next-day delivery volumes by 15%.

Teo, Ou and Goh (2001) study the impacts of consolidating several regional distribution centers into one central distribution center on the facility investment and inventory costs. They propose a location model that captures the impact of the inventory-related costs. Stochastic demands are assumed at customer locations. As a result of their analysis, they conclude that consolidation leads to lower total facility investment and inventory costs if the demands are identically and independently distributed, or when they follow independent but possibly nonidentical Poisson processes. However, they show by an example that consolidation can be infinitely worse off than the optimal decentralized system for the general demand processes.

Snyder, Daskin and Teo (2002) present a stochastic version of the location model developed by Daskin, Coullard and Shen (2000), and Daskin, Coullard and Shen (2002). Although location model with risk pooling model (LMRP) incorporates stochastic demands that follow a normal distribution by assuming stationarity of the demand distribution, it fails to take into account the changing environment in which the supply chain will operate. A stochastic version of LMRP (SLMRP) is proposed in this study that handles parameter uncertainty by allowing parameters to be described by discrete scenarios, each with a specified probability of occurrence. The SLMRP is a two-stage model, in that strategic decisions (facility location) must be made before it is known which scenario will come to pass, while tactical decisions (assignment of retailers to distribution centers, setting inventory levels) are made after the uncertainty has been solved. Hence, the location decisions are scenario-independent, and assignment decisions are scenario-dependent. There are two levels of randomness in SLMRP: scenarios determine the means and variances of the demands, but once the scenario has been realized, demands are still random according to the specified normal distribution. The goal of the model is to minimize the expected cost of the system. A Lagrangian relaxation algorithm, similar to the one developed for LMRP, is proposed for that nonlinear integer model. Also, a branch and bound procedure is applied to close the gap, if any, after the Lagrangian procedure. 3, 5, and 9 scenario problems are generated on the 3 chosen data sets to test the algorithm. When the stochastic solutions with the deterministic individual scenario solutions are compared, it is seen that they differ substantially in their choices of distribution center locations. Also, it is observed that some retailers – roughly half on average, but up to 97%- are assigned to different distribution centers in different scenarios, indicating the importance of allowing retailer assignments to be scenario dependent. This suggests that each of the deterministic individual scenario solutions would perform poorly in long-run expected cost. They also describe how to use the SLMRP framework to model multi-commodity problems.

2.2. Heuristic Location Algorithms

Location models are often extremely difficult to solve, at least optimally. Even the most basic models such as *p*-median, *p*-center, and maximal covering are computationally intractable for large problem instances. In fact, the computational complexity of location models is a major reason that the widespread interest in formulating and implementing such models did not occur until the advent of high-speed digital computers (Current, Daskin and Schilling, 2002). Due to these facts, location analysts have developed heuristic algorithms to find at least very good solutions. Among these, a number of heuristic algorithms for solving *p*-median problems as well as uncapacitated fixed charge facility location models have been proposed and have demonstrated outstanding performance (See Daskin (1995) for the heuristic algorithms for location problems).

Heuristic solution methods for location/allocation problems have a number of advantages when compared with exact programming techniques: large problems can be solved relatively quickly; many objective functions can be used; and a range of alternative, marginally suboptimal solutions can be identified (Densham and Rushton, 1992). Also, due to their simple structure and relatively low computation times, heuristic methods can allow for sensitivity and robustness analyses, which would probably be very important for a decision maker, who is required to evaluate many aspects and effects of the decisions when confronted with a strategic problem. The major drawback of heuristic solutions is that they are not exact; none can be guaranteed to find the optimum solution.

The literature devoted to heuristic location algorithms often distinguishes between two broad classes: **improvement algorithms** and **constructive algorithms**. Improvement algorithms generally start with a feasible solution and iterate to obtain a better solution. In order to use improvement heuristics, one must decide how to obtain the initial solution. Initial solutions can be generated randomly or by using the result of a greedy heuristic. When a series of randomly generated solutions are used, the best solution among all of the local optima found is selected as the one to be implemented. On the other hand, a constructive algorithm builds a solution from scratch by adding individual components (e.g., nodes, arcs, variables) one at a time until a feasible solution is obtained. In this method, the first facility is located in such a way that the total cost is minimized. Then the facilities are added one by one, each time selecting the location that most reduces the total cost. The algorithm terminates at the point when the total cost starts to increase. Also, some neighborhood heuristics can be applied to improve on the solution found using constructive algorithms.

We use some local search type algorithms in the improvement type heuristic that we develop to solve our problem. Neighborhood/Local search algorithms are a wide class of improvement algorithms where at each iteration an improving solution is found by searching the neighborhood of the current solution. One solution is a neighbor of another solution if it can be obtained by adding or deleting or changing the location of a facility, and by reallocating the demands to different facility sites. In case the neighborhood of the solution does not contain any solution better than itself, local search returns the current solution and terminates. This method does not guarantee globally optimal solutions to most combinatorial problems, but generally returns relatively good quality solutions (Ghosh, 2003; Hansen and Mladenovic, 1997).

The neighborhood search algorithm developed by Maranzana (1964) for the p-median problem is one of the earliest improvement heuristics. In this method, the algorithm begins with any feasible solution or specifically a set of p facility sites. Demand nodes are then assigned to their nearest facility and the set of nodes assigned to a facility forms a cluster around that facility. Then 1-median problem can be solved optimally within each cluster by enumeration method for each facility location. Then the procedure is iterated with the new location of the facilities until no more changes in the assignments occur. The most widely known improvement heuristic for *p*-median problem is introduced by Teitz and Bart (1968). In this method, a facility is moved from the location it occupies in the current solution to an unused site. Each unused location is tried in turn and when a move produces a better objective function value, then that relocation is accepted and an improved solution is obtained. The search process iterates on the new solution until no better solution can be found by this method. This procedure is known as an "interchange", "exchange", or " substitution" heuristic, since it exchanges an open site with one of the unused sites.

The most efficient implementation of the exchange algorithm is presented by Whitaker (1983). In Whitaker (1983), three efficient ingredients are incorporated in the interchange heuristic: (i) move evaluation, where a best removal of a facility is found when the facility to be added is known; (ii) updating the first and the second closest facility of each user; (iii) first improvement strategy, where each facility is considered to be added only once.

We can use a number of alternative strategies while implementing improvement heuristics. For instance, in the exchange heuristic of Teitz and Bart (1968), every time an exchange is found that yields a better solution, the solution set is updated and the search process is restarted and applied to the new solution set. Alternatively, one can select the best solution after considering all possible moves for a given facility site, or choose the best after all possible exchanges for each of the sites are examined. Applying different search strategies influences the computational speed of the heuristic and may also affect the quality of the solution.

Our problem is similar in structure to the problems in the literature that include warehouse operating costs in their models. Since big warehouses are more `efficient` than small ones, total warehousing costs will rise as the number of warehouses is increased. Since shipping costs decrease as the number of warehouses is increased, the problem of minimizing total cost is to balance against warehouse operating costs (Feldman, Lehrer and Ray, 1966). There are some constructive type heuristic algorithms proposed to solve this kind of problems and they are stated to be flexible algorithms with respect to the kind of warehousing cost function allowed and can accommodate widely varying cost structures and parameters among the different warehouse sites. Some of the authors who propose heuristics for solving non-linear warehouse location problems are Kuehn and Hamburger (1963), Feldman, Lehrer and Ray (1966), Khumwala and Kelly (1982), and Whitaker (1985). These heuristic techniques can generate near optimal solutions to large-scale warehouse location problems having continuous nonconvex warehousing cost functions (Feldman, Lehrer, Ray, 1966).

2.3. Joint Replenishment Problem (JRP)

Although single-item models are analyzed in most of the literature on inventory theory, in practice one often needs to determine stocking policies for multiple items. The problem of coordination in the replenishment of multiple products when they share common resources (i.e. the same mode of transportation or the same stocking location), with the idea of benefiting from the savings in major ordering costs can be observed in many supply chains. The economic incentive behind the joint replenishment of a group of items lies in the fact that if each item is replenished individually, major ordering cost is associated with each of these individual item replenishments. Also, as Viswanathan (1996) points out, the JRP is relevant only when the major ordering cost is moderate. When major ordering cost is very low, applying independent EOQ systems for each item would be as cost effective as a coordinated system. When major ordering cost is very high, it is best to replenish all the items together and consider only a single EOQ model.

Special attention has been given to the JRP in the literature for the last three decades. A survey of algorithms can be found in Aksoy and Erenguc (1988) and

Goyal and Satir (1989). Nevertheless, few studies considering a multi-item environment relate the JRP to the developed mathematical models for real supply chains (Muckstadt and Roundy, 1987; Viswanathan and Mathur, 1997; Qu, Bookbinder and Iyogun, 1999)

Inventory models related to JRP literature basically fall in two main categories according to the nature of demand: deterministic and stochastic models. In the deterministic methods it is assumed that the major ordering cost is charged at a basic cycle time T and that the ordering cycle of each item is some integer m_i multiple of T, which is called a (m_i, T) policy. In this line of research Goyal (1974) propose a solution method for the JRP based on enumeration where the running time of the procedure grows exponentially with the number of items, and therefore the method is only suitable for small problem instances. Moreover, he does not specify bounds for the problem and therefore one cannot test for optimality. Wildeman, Frenk and Dekker (1997) present a more suitable optimal solution method for larger problems based on Lipschitz optimization. Other authors focused on heuristic procedures most of which are based on setup-to-holding cost ratios for each item (Silver, 1976; Goyal and Belton, 1979; Kaspi and Rosenblatt, 1983). Kaspi and Rosenblatt (1983) investigate the effectiveness of different heuristic algorithms by using a simulation program. Also using a sorting algorithm, Jackson, Maxwell, and Muckstadt (1984) present an efficient procedure for the JRP under the restriction that the reorder intervals must be a power of two times a base period length.

The development of decision rules for coordinated items under stochastic demand is not an easy task (Aksoy and Erenguc, 1988). Continuous review and periodic review models are developed for the stochastic JRP. In the stochastic arena, Balintfy (1964) first introduces the use of (S,c,s) systems or “can-order” systems, in which items are replenished up to level S if they reach a reorder level s. Coordination is achieved by including in the order any other item of the same family whose inventory level is below its can order level c. Later, Silver (1974) proposes a method to determine in an optimal way the parameters of the (S,c,s) system. Although this policy performs relatively well, Ignall (1969) shows that optimality cannot be guaranteed. Periodic review policies perform better than continuous review can-order policies in terms of total cost except when the major ordering cost is close to zero (Silver, Pyke and Peterson, 1998). Atkins and Iyogun (1988) propose the use of periodic replenishment policies, where all items or specific subsets of them are ordered in every replenishment opportunity up to a base stock level *S*. The objective is to select optimal values of the review time and the order up to level *S*. They also suggest modified periodic review policy where the review intervals for the items differ and a varying number of items will be jointly ordered in each period. For the set of problems used in their computational test, periodic review policies perform better than the continuous review can-order policies. In the periodic review joint replenishment policies suggested by Atkins and Iyogun (1988), the items are ordered periodically irrespective of their inventory positions. Viswanathan (1997) analyses a periodic review P(*s, S*) policy, where the inventory positions of all items are reviewed once every *R* units of time, and item k is ordered up to level S_k, if its inventory position is less than or equal to s_k at the time of the review. In their method, the review interval (*R*) is a decision variable and they attempt to find the best value of *R* by searching for different values of *R*. Viswanathan (1997) also compares the solutions of the P(*s, S*) policy with those of the other policies in the literature, and finds that P(*s, S*) policy give solutions that generally dominates other policies.

Having reviewed the studies about the distribution design problems, solution methods and joint replenishment policy, we define our multi-item integrated location/inventory problem in the following chapter.

CHAPTER 3

ANALYSIS OF THE INTEGRATED LOCATION/INVENTORY PROBLEM

3.1. Description of the System and Definition of the Problem

In this study, we consider the design of a distribution system, in which a single supplier ships a number of items to the retailers via a number of distribution centers. The locations of the single supplier and the retailers are assumed known and fixed. Associated with each retailer, there is some random demand for all the items. We assume that the demands at each retailer are uncorrelated among different types of items. Also, independent demand is assumed across retailers for all types of items. Due to the variable demand at the retailers, some amount of safety stock is held therein to achieve suitable service levels. To take the advantage of risk pooling, some of the retailers are set as distribution centers. Then safety stock for all retailers served by a distribution center is assumed to be maintained at the distribution center. Therefore, less total safety stock is required than in the case where every retailer maintains its own safety stock. Centralizing inventory reduces both safety stock and average inventory in the system (Simchi-Levi, Kaminsky, Simchi-Levi, 2000).

All of the retailers are considered to be candidate locations for distribution centers. Alternatively, only a subset of retailers can be considered as the distribution center candidates. A retail location, which is chosen as a distribution center, orders the items from the supplier and distributes them to the other retailers, assigned to itself. The graphical representation of the distribution network is provided in Figure 3.1.

Single source constraints are imposed on the assignment of the retailers to the distribution centers. That is, each retailer should be assigned to one and only one open distribution center and all the demand of a retailer is satisfied by a single distribution center. Also, when a distribution center is located at a retailer location, the demand occurred at that retailer is replenished by the distribution center opened at the same location; that is, if there is a DC at a retailer location, it must serve the demand that occurs at that location.

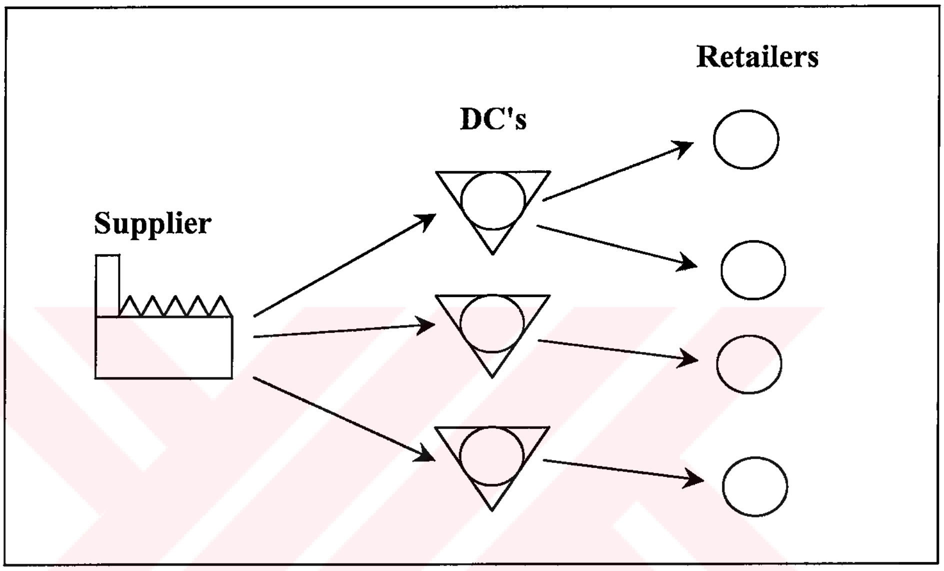

Figure 3.1: Representation of the Distribution System

Capacity restrictions are not considered at any level of this distribution system. That is, the single supplier in the system is assumed to have infinite supply for all items. Also, distribution centers are assumed to be uncapacitated; therefore, single source restrictions imposed on the assignment of retailers to the distribution centers do not create any problem in terms of capacity. Due to the single source constraints and no capacity restrictions, the assignment of retailers to the distribution centers can be considered as if there is only one item in the system. The model with single source constraints may result in achieving less benefit from risk pooling across items compared to the model without such constraints. However, it is still likely that high demand from one retailer for an item is offset by low demand from another and thus the advantage of consolidating demand for items at the distribution centers is obtained.

Satisfying a customer's demand from a single distribution center is frequently justified in practice because this results in economic advantages due to increased economies of scale in distribution center-to-retailer shipments, decreased administrative costs and more convenient service levels (Geoffrion and Graves, 1974).

Each distribution center can maintain and distribute all the items; that is, there is no restriction for an opened distribution center on the type of the item it can keep and distribute. There may be plenty of items in the system requiring the precise control of inventory levels. Although daily operation of inventories may require item-level control, long-term planning of the inventory can be accomplished by substantially aggregating items into broader groups. Alternatively, a number of representative items can be selected over a range of key dimensions such as demand, size, weight, and manufacturing cost for simplification (Daskin, 1985). Therefore, we assume that all the items are grouped into a manageable number of item groups. That is, a number of item groups is considered rather than all items at individual level.

In this multi-item distribution system, the distribution centers replenish their inventories by ordering each item from the single supplier. A multi-item inventory system is assumed at each distribution center. By implementing a multi-item inventory system, each distribution center should determine the items that should be procured on each order and the ordering interval for each item. A multi-item inventory system is usually characterized by some interaction among the items. Savings in the ordering cost may result when several items are ordered simultaneously or when several items are replenished from a single supplier. The economic incentive behind the desire for joint ordering of the items as a group lies in the fact that, if each item is replenished individually, major ordering cost is associated with each of the individual replenishments. Assuming that the major ordering cost at each distribution center is neither very high nor low which would otherwise encourage us to replenish all items together or separately, respectively, a joint replenishment policy is assumed to be implemented at each distribution center to benefit from the savings that may result from consolidating the requirements of different products in a single order under moderate level of major ordering costs.

We also consider the fixed cost of locating distribution centers at retailer sites and shipping costs due to moving of items from the distribution centers to the retailers (outbound transportation), as well as from the supplier to the distribution centers (inbound transportation). Shipping costs are both item and distance dependent. Fixed facility costs include the expenditures for establishing the facilities, such as the investments in buildings and equipment. Moreover, some locational factors may affect fixed facility costs such as land value, energy costs, property taxes and insurance rates.

In this distribution design problem, the objective is to investigate the optimal balance between facility establishment, transportation and inventory decisions and to analyze the trade-offs among these functions of the distribution system. For example, as the number of distribution centers increases, transportation costs are expected to decrease while inventory costs increase. Moreover, the costs are dependent on the location and demand characteristics of the retailers.

Given this background, we can state the problem as follows: Given a collection of retailers, each with uncertain demand for a number of items, determine how many distribution centers to locate, where to locate and which retailers to assign to each distribution center such that the sum of facility costs, inbound and outbound transportation costs, joint ordering and average inventory costs, and safety stock costs is minimized while ensuring a specified level of service at the retailers for each item.

3.2. Inventory Policy at the Distribution Centers

The physical distribution of inventory is an extremely important problem for any organization. The profit potential for improved system design and inventory control is considerable, as well as the challenges. One such challenge is posed by the uncertainties inherent in these systems, principally customer demand uncertainties. Another important challenge is the fact that system performance and cost depend in large part on the interaction between the physical system design and the inventory control system (Schwarz, 1981). For example, the location of distribution centers and the allocation of the retailers to the distribution centers have a significant effect on the total inventory investment, inventory distribution, and customer service. On the other hand, the production/inventory policies used to operate a system can have a significant effect on the design parameters of the physical system.

The main aim of an effective inventory policy in a supply chain should be to ensure that the right levels of stock are held in the right place at the right time. To achieve a high customer service level, some amount of inventory must be held as a buffer against the variability in demand. Holding large amounts of inventory allows a company or an entire supply chain to be very responsive to fluctuations in customer demand. However, the creation and storage of inventory is a cost and to achieve high levels of efficiency, the cost of inventory should be kept as low as possible.

We assume a periodic review system at the DCs. In the situations where the coordination of the replenishments is attractive, a periodic review policy is particularly appealing, because all items in a coordinated group can be given in the same review interval (Silver, Pyke and Peterson, 1998, p.236). We assume that a modification of the periodic review (R,S,s) policy is implemented at each DC. In the usual form of an (R,S,s) policy, the inventory position of an item is checked every R units of time. If the inventory position of the item is at or below the reorder point s, an order is given enough to raise the inventory level to the order-up-to-point S. If the inventory position is above s, nothing is done until at least the next review. Although it is shown that under quite general assumptions, the best (*R,S,s*) system produces a lower sum of replenishment, carrying, and shortage costs than does any other system, the computational effort to obtain the best values of the three control parameters is more intense than that for other systems (Silver, Pyke and Peterson, 1998, p. 241).

For the problems with multiple items, Atkins and Iyogun (1988) propose the use of (*R, S*) type periodic replenishment policies, where all items are ordered in every replenishment opportunity up to a base stock level *S*. The objective is to select optimal values of the review time (*R*) and the order up to level (*S*). They also suggest "modified" (*R, S*) type periodic review policy where the review intervals for the items differ and a varying number of items are jointly ordered in each period. In these periodic review joint replenishment policies, the items are ordered periodically irrespective of their inventory positions. Also, Qu, Bookbinder and Iyogun (1999) use a "modified" (*R, S*) type policy in their study, which considers an integrated inventory/transportation system with multiple-items. Viswanathan (1997) states that more flexibility can be achieved by ordering any particular item only if its inventory position warrants it and analyses a periodic review (*R,S,s*) policy for multiple items. In this policy, the inventory positions of all items are reviewed once every *R* units of time, and item *k* is ordered up to level S_k if and only if its inventory position is less than or equal to s_k at the time of the review. Viswanathan finds the initial value of *R* by solving the deterministic version of the JRP and attempts to find the best value of *R* by searching for different values of *R*. Then optimal values of *s* and *S* for each item are computed by using the algorithm of Zheng and Federgruen (1991).

In this study, we propose the use of a "modified" periodic review (*R,S,s*) policy. Our "modified" (*R,S,s*) policy can be considered as an extension of the multi-item (*R,S,s*) policy proposed by Viswanathan (1997). In the "modified" periodic review (*R,S,s*) policy, the review interval of each item (R_k) may differ and each R_k is an integer multiple of the base review interval *R*. Then inventory positions of only a group of items are checked every *R* units of time and item *k* is ordered up to level S_k, if its inventory position is less than or equal to its reorder point s_k. Therefore, a varying group of items is jointly ordered in each review period (R).

Because of the complexity of the exact analysis of the (R,S,s) multi-item inventory policy, we approximate the "modified" periodic review (R,S,s) policy for our multi-item problem by assuming that the demand is deterministic. Then it is assumed that the DCs order inventory from the supplier using the approximate solution, which is provided by the deterministic model with Type I service constraint. The analysis of the deterministic model and its implementation are presented in §3.2.2.

3.2.1. Types of Inventories at the Distribution Centers and the Risk Pooling Effect

As mentioned before, some amount of inventory is maintained at the distribution centers. It is assumed that the retailers maintain only a small amount of inventory. This is because the retailers are replenished frequently (daily for example) with relatively small batches by the distribution centers in most of the fast-moving consumer goods industry. Therefore, we ignore the inventory costs that is incurred at the retailers in our study. The inventory maintained at the distribution centers includes both cycle (average) inventory and safety stock inventory. Cycle inventories result from an attempt to order in batches instead of one unit at a time. The amount of inventory on hand, at any point, that results from these batches is called the cycle stock. The amount of cycle stock on hand at any time depends directly on how frequently orders are placed (Silver, Pyke and Peterson, 1998, p.30). Companies tend to produce and purchase in large lots in order to gain the advantages that economies of scale can bring by reducing ordering costs. Ordering costs include clerical and other processing costs associated with order preparation or receipt, which are independent of the quantity ordered. However, large lots give rise to increased carrying costs, which include the cost of capital on purchased goods, cost to store, handle, and insure the inventory. The trade-off exists between the reduced cost of ordering by purchasing items in large lots, and the increased carrying cost of the cycle inventory that comes with purchasing in large lots. In our problem, the average inventory to be maintained at each distribution center is found by the application of a joint replenishment policy, which considers the trade-off between the ordering and carrying costs in a similar way that EOQ does. The details about the joint replenishment policy are presented in the next section.

Safety stock inventory is held as a buffer against uncertainty in demand. Safety stocks are not needed when the future rate of demand and the length of time it takes to get complete delivery of an order are known with certainty. The level of safety stock is controllable in the sense that this investment is directly to the desired level of customer service (Silver, Pyke and Peterson, 1998, p.31). The trade-off here is to weigh the costs of carrying extra inventory against the costs of losing sales due to insufficient inventory.

An important and commonly used service level measurement in inventory systems is the stockout rate, which is the percentage of demand that cannot be satisfied from on hand inventory. In the presence of uncertain demand, safety stock is carried to reduce the stockout rate (or to increase the fill rate).

As mentioned before, in our problem, the safety stock required is assumed to be maintained only at the distribution centers to achieve the benefits of risk pooling. Centralizing inventory results in reduced safety stock inventory in the system. Therefore, less total safety stock is required than in the case where every retailer maintains its own safety stock. Other benefits of centralizing inventory beyond the reduced inventory costs can be stated as follows (Teo, Ou and Goh, 2001):

- *Reduced facility investment costs*: A large distribution center is more cost efficient to build and operate compared to having many smaller stocking points (the effect of economies of scale).
- *Increased service quality*: Centralized inventory ensures better quality control and visibility of stocks within the system.

On the other hand, having smaller number of distribution centers increases the cost of transporting items to the retailers and delivery times to the customers.

Risk pooling concept suggests that demand variability is reduced by the aggregation of demand. It becomes more likely that high demand from one retailer will be offset by low demand from another. The reduction of variability by demand aggregation allows reducing safety stock and therefore reducing total inventory costs. The reallocation of inventory is not possible in a decentralized distribution system. Eppen (1979) shows the benefit of centralizing inventory in a multi-location newsboy problem with N retailers. Associated with each retailer, there is normally distributed customer demand with a mean of μ_i, and a standard deviation of σ_i for retailer i. Eppen demonstrates that the expected cost of a decentralized system is $K\sum_{i=1}^{N}\sigma_i$, whereas the expected cost of a centralized system can be expressed as $K\sqrt{\sum_{i=1}^{N}\sigma_i^2}$ when the demands of the N retailers are independent. K is a constant depending on the holding and penalty costs and the standard normal loss function. Since the expected cost of the centralized system is less than that of the decentralized system, we have the risk pooling incentive for centralizing inventories.

In order to see the effects of risk pooling on safety stock inventory, assume that we know the set of retailers assigned to the distribution center j. Let S_j represent the set of retailers assigned and replenished by the distribution center j. Also, assume that the demand for item k at retailer i is normally distributed with a mean of μ_{ik}, and a standard deviation of σ_{ik}. Then if the lead time from supplier to the distribution center j is L_j, the lead time demand for item k at distribution center j is normally distributed with a mean of $L_j \sum_{i\in S_j} \mu_{ik}$ and a variance of $L_j \sum_{i\in S_j} \sigma_{ik}^2$, assuming that the retailer demands are independent. Thus, the safety stock inventory to maintain a service level of α_k for item k at distribution center j, is given by $z_{\alpha_k}\sqrt{L_j \sum_{i \in S_j} \sigma_{ik}^2}$,

where z_{α_k} is a standard normal deviate such that $P\left(z \le z_{\alpha_k}\right) = \alpha_k$. Then under constant lead times, the safety stock of an item is proportional to the standard deviation of the item's demand supplied by the distribution center.

Consider the following case with five retailers and two items. In Figure 3.2, in the decentralized system, each of the five retailers replenishes themselves for both items. Assuming constant lead times and the same service level for all items, the total safety stock maintained for item 1 is proportional to:

$$\left(\sigma_{12} + \sigma_{22} + \sigma_{32} + \sigma_{42} + \sigma_{52}\right)$$

, and the safety stock maintained for item 2 is proportional to:

$$\left(\sigma_{11} + \sigma_{21} + \sigma_{31} + \sigma_{41} + \sigma_{51}\right)$$

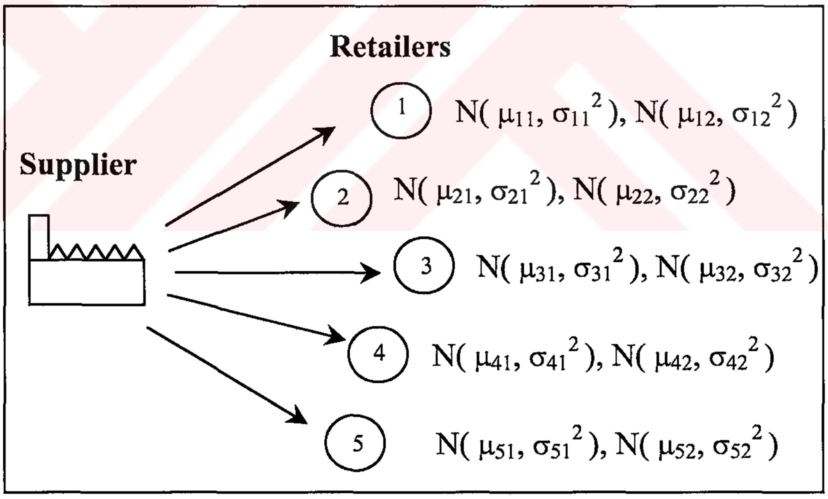

Figure 3.2: Representation of the Decentralized System

When a distribution center is located at retailers 2 and 4, as shown in Figure 3.3, the total safety stock maintained for item 1 is proportional to:

$$\sqrt{\sigma_{11}^2 + \sigma_{21}^2 + \sigma_{31}^2} + \sqrt{\sigma_{41}^2 + \sigma_{51}^2}$$

, and the safety stock maintained for item 2 is proportional to:

$$\sqrt{\sigma_{12}^2 + \sigma_{22}^2 + \sigma_{32}^2} + \sqrt{\sigma_{42}^2 + \sigma_{52}^2}$$

which is less than that of the decentralized case.

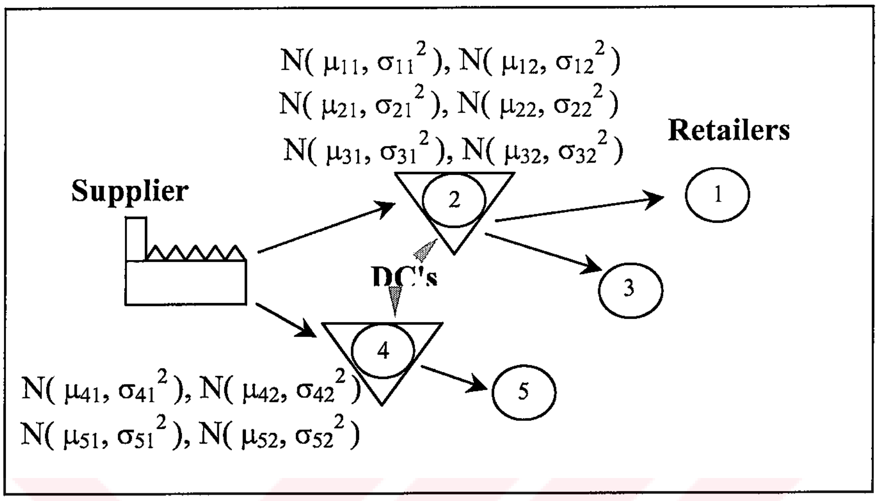

Figure 3.3: Representation of the Centralized System

3.2.2. Joint Replenishment Problem (JRP)

The JRP is an inventory problem concerning a multi-item system. In an inventory system with multiple items, cost savings can be achieved when the replenishment of several items is coordinated. Inventory models related to the JRP basically fall in two main categories according to the nature of demand: deterministic and stochastic models. The starting assumption under deterministic models is that the demand rate for each item and the lead times are deterministic.

In our study, we handle the JRP at the distribution centers by assuming that the demand is deterministic, since coordinated control of items with probabilistic demand complicates the decision problem, as also noted by Silver, Pyke and Peterson (1998, p.434). As a result, the solution to the deterministic JRP turns out to be an approximate solution to the real stochastic JRP in our integrated location/inventory problem.

In the deterministic JRP, a specific joint setup cost which is a major setup cost (fixed cost of placing an order) is incurred for each order, irrespective of the number of distinct items involved in the order. Additionally, an item specific (minor) setup cost is incurred for each specific item that is included in the order. Joint replenishment of a group of items reduces the number of times the major ordering cost is charged and hence reduces the costs. The optimization criterion in the JRP studies is the long-run average cost.

Assumptions:

We use the following assumptions in the derivation of the deterministic JRP model due to Silver, Pyke and Peterson (1998, pp.425-426):

1. The demand rate of each item is constant and deterministic.
2. The replenishment quantities of the items need not be integer.
3. The unit variable cost does not depend on the number of units included in the replenishment; that is, there are no quantity discounts in the purchase cost and the unit shipping costs.
4. The lead time is known.
5. No shortages are allowed.
6. The entire order quantity is delivered at the same time.

Notation:

k : index for items

K : total number of items

A : major ordering cost per order

a_k : minor ordering cost for item k

D_k: demand rate of item k

c_k : unit variable cost of item k

I : the inventory carrying charge

T: basic cycle time

m_k: the integer number indicating the frequency (number of cycles, T) at which item k is ordered

TRC: total cost of replenishment, composed of ordering and holding costs

In the deterministic JRP, the major ordering cost (A) is assumed to be charged at a basic cycle time (T), and the ordering cycle of each item is some integer multiple of this basic cycle. In this policy, item k will be included in every m_k^{th} replenishment, just as its inventory hits the zero level. The selection of the values of T and m_k's is the aim of the deterministic JRP. The inventory behaviour of three items that are jointly replenished is illustrated in Figure 3.4. According to the figure, item 1 is included every time an order is placed, while items 2 and 3 are included in the replenishment every other time.

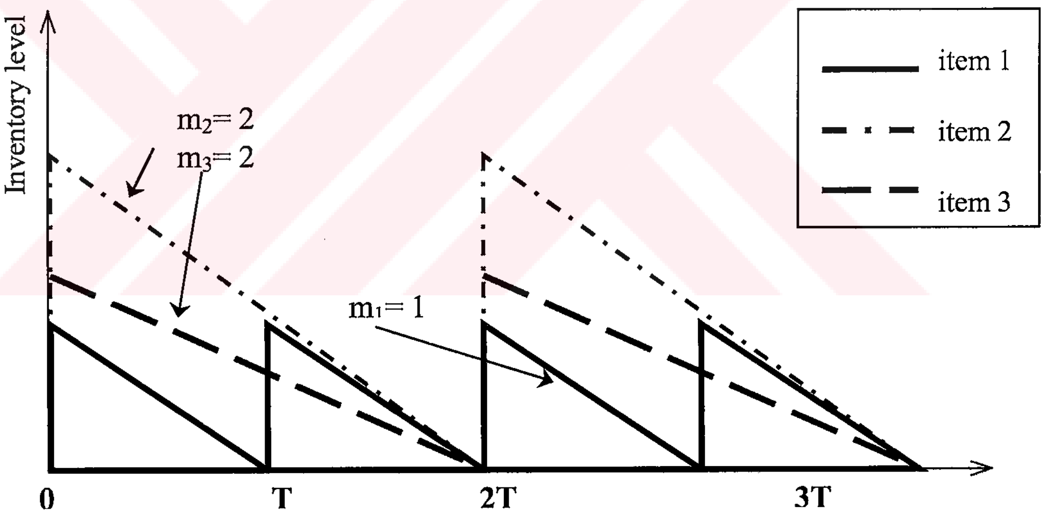

Figure 3.4: Inventory Behaviour of Three Items Jointly Replenished

For the deterministic JRP total cost per unit time is given by:

$$TRC(T, m_k\text{'s}) = \frac{A}{T} + \frac{1}{T}\sum_{k=1}^{K}\frac{a_k}{m_k} + \frac{T}{2}\sum_{k=1}^{K}\left(D_k m_k c_k I\right) \qquad \textbf{(3.1)}$$

In this total cost function, there are (K+1) decision variables. One of them is the continuous variable, T, and the other K variables (m_k's) are integers.

As mentioned before, our aim in this study is to integrate inventory decisions with strategic location/allocation decisions for this multi-item distribution system. However, although we simplify the JRP by assuming that the demand is deterministic, incorporating this joint replenishment policy in the location/allocation problem would make the integrated location/inventory model still difficult to handle in terms of the number of decision variables and the cost structure. Note that, the number of decision variables related to JRP increases with the increase in the number of distribution centers, since the inventory policy followed at each distribution center may be different depending on the composition of demand assigned to the distribution center and the values of major and minor ordering costs specific to a distribution center. Moreover, in order to evaluate the joint replenishment policy at the distribution centers, we have to know the number and location of the distribution centers, as well as how much demand of each item is assigned to a specific distribution center. In other words, the inventory allocation decisions depend on the location/allocation decisions. Also, we aim to solve the location/allocation problem by considering the effects of the joint replenishment policy; therefore, location allocation decisions are also dependent on the inventory policy followed at the distribution centers.

Considering the strategic nature of the location decisions and the tactical and operational characteristic of inventory allocation decisions, it is wise to use some approximations/simplifications to represent the inventory policies to be followed at the distribution centers. Therefore, we are only interested in the cost implications of the joint replenishment policy addressing a strategic problem in the supply chain; therefore, we are not solving for the exact inventory control parameters.

Fortunately, using the following heuristic procedure for the JRP, which is presented in Silver, Pyke and Peterson (1998, pp.427-428), a lower bound (LB) for the cost of the best (T, m_k's) policy can be found.

Heuristic for the LB for the Cost of JRP:

S1. Rank the items such that

$$\frac{a_k}{D_k c_k} \text{ is smallest for item 1. Set } m_1 = 1.$$

S2. Evaluate

$$m_k = \sqrt{\frac{a_k}{D_k c_k} \frac{D_1 c_1}{A + a_1}} \qquad k = 2, 3 \ldots, K \qquad \textbf{(3.2)}$$

rounded to the nearest integer greater than zero.

S3. Using the m_k's found in S2, evaluate T* (best T for a particular set of m_k's).

$$T^*(m_k\text{'s}) = \sqrt{\frac{2\,(A + \sum \frac{a_k}{m_k})}{I \sum m_k D_k c_k}} \qquad \textbf{(3.3)}$$

S4. Determine replenishment quantity of each item by evaluating

$$Q_k = m_k D_k T^* \qquad k = 1,2, \ldots, K$$

In order to obtain the LB for the cost of the best (T, m_k's) policy, the following algebra is applied (See Silver, Pyke and Peterson (1998, pp.453-457) for the details):

Equation 3.3 is substituted into equation 3.1 to obtain the best cost for a given set of m_k's:

$$TRC^*(m_k\text{'s}) = \sqrt{2\,(A + \sum \frac{a_k}{m_k})\, I \sum m_k D_k c_k} \qquad \textbf{(3.4)}$$

Then we substitute $m_1 = 1$ and the generally noninteger m_k's of equation 3.2 into equation 3.4. This leads, after considerable algebra, to the following LB for the best possible total cost of JRP:

$$TRC_{bound} = \sqrt{2\,(A + a_1)D_1 c_1 I} + \sum_{k=2}^{K} \sqrt{2 a_k D_k c_k I} \qquad \textbf{(3.5)}$$

The first term of the lower bound is the total cost per unit time of an EOQ strategy when item 1 considered alone, if we associate the major ordering cost (A) with each replenishment of item 1. Item 1 is included in every replenishment in the optimal policy; that is, the ordering interval for item 1 is the basic cycle time, T. From now on, item 1 will be referred as the *base item*. The second term represents a summation of the total cost per unit time of an EOQ strategy for each of the other items, where only minor ordering cost is associated with the replenishment of these items. Allocation of the major ordering cost among the items was also suggested by Atkins and Iyogun (1987, 1988). Their method partitions the items into two groups: base items and nonbase items. The base items are those for which $m_k = 1$, hence are replenished every time any of the K items is replenished. This scheme is also used by Qu, Bookbinder, and Iyogun (1999) in their heuristic algorithm to solve an integrated inventory-transportation problem.

As noted, the base item is determined in the first step of the heuristic procedure described above. The items are ranked by their ratio of $\left(\dfrac{a_k}{D_k c_k}\right)$, and the item, which makes this ratio smallest, is chosen as the base item. We should note that, setup-to-holding cost ratio was frequently used by the authors who developed heuristic procedures to solve JRP. For instance, $(\dfrac{a_k}{D_k h_k})$ and $\left(\dfrac{A + a_k}{D_k h_k}\right)$ ratios were used for the determination of the base items by Silver (1976), and Goyal and Belton (1979), respectively, where h_k represents the unit holding cost for item k.

Assuming that the results provided by the deterministic joint replenishment policy are implemented at the DCs, the "modified" (R,S,s) type periodic review inventory policy for multiple items is realized in practice in the following way. The base review interval (R) is set to basic cycle time (T) found in equation (3.3). Then review interval of each item (R_k) is determined as an integer multiple, m_k, of the basic cycle time (T). That is, item k is reviewed every m_kT periods of time and replenished up to its order-up-to-level, S_k, if its inventory position is less than or equal to s_k. The average order size found as $Q_k = m_k D_k T^*$, which is an approximation for the amount of replenishment for item k. That is, it approximates the difference between the order-up-to level of item k, S_k, and the inventory position of item k, if an order is given for the item at its review time.

3.3. Mathematical Model for the Multi-Item Integrated Location/Inventory Problem

The following notation is used in the model formulation:

Indices:

k: index for the set of items $(k = 1,\ldots,K)$

i: index for the set of retailers $(i = 1,\ldots,I)$

j: index for the set of candidate DC locations $(j = 1,\ldots,J)$

Parameters:

f_j : fixed annualized cost of locating a DC at candidate location j, for each $j \in J$

d_{ijk} : unit cost to ship item k from the DC located at candidate location j to retailer i, for each $i \in I, j \in J$ and $k \in K$

c_{jk} : unit cost to ship item k from the supplier to the DC located at candidate location j, for each $j \in J$ and $k \in K$

μ_{ik} : mean annual demand of item k at retailer i, for each $i \in I$ and $k \in K$

σ_{ik}^2 : variance of annual demand of item k at retailer i, for each $i \in I$ and $k \in K$

L_j : lead time (in years) from the supplier to the DC located at candidate location j, for each $j \in J$

h_k : inventory holding cost per unit of item k per year, for each $k \in K$

A_j : major ordering cost at the DC located at candidate location j, for each $j \in J$

a_{kj} : minor ordering cost of item k at the DC located at candidate location j, for each $j \in J$ and $k \in K$

α_k : desired probability of not stocking out at a DC for item k, for each $k \in K$

z_{α_k}: standard normal deviate such that $P(z \le z_{\alpha_k}) = \alpha_k$, for each $k \in K$

Decision variables:

$$X_j = \begin{cases} 1, & \text{if a DC is located at candidate location } j \\ 0, & \text{otherwise} \end{cases}$$

$$Y_{ij} = \begin{cases} 1, & \text{if retailer } i \text{ is served by a DC located at candidate location } j \\ 0, & \text{otherwise} \end{cases}$$

The mathematical model representing the multi-item integrated location/inventory problem is as follows:

Minimize

$$\sum_{j=1}^{J} f_j X_j + \sum_{j=1}^{J}\sum_{i=1}^{I}\sum_{k=1}^{K} d_{ijk}\mu_{ik}Y_{ij} + \sum_{j=1}^{J}\sum_{i=1}^{I}\sum_{k=1}^{K} c_{jk}\mu_{ik}Y_{ij} +$$

$$\sum_{j=1}^{J}\sum_{k=1}^{K} h_k z_{\alpha_k}\sqrt{\sum_{i=1}^{I} L_j \sigma_{ik}^2 Y_{ij}} + \sum_{j=1}^{J}\sum_{k=1}^{K}\sqrt{2R_{kj}h_k\sum_{i=1}^{I}\mu_{ik}Y_{ij}} \quad \textbf{(3.6)}$$

subject to

$$\sum_{j=1}^{J} Y_{ij} = 1 \qquad \forall i \qquad \textbf{(3.7)}$$

$$Y_{ij} \le X_j \qquad \forall i,j \qquad \textbf{(3.8)}$$

$$X_j \in \{0,1\} \qquad \forall j \qquad \textbf{(3.9)}$$

$$Y_{ij} \in \{0,1\} \qquad \forall i,j \qquad \textbf{(3.10)}$$

where $R_{kj} = A_j + a_{kj}$, if k is base item for DC candidate j **(3.11)**

$R_{kj} = a_{kj}$, if not **(3.12)**

In the notation and the model above, the time horizon of the model is assumed to be one year. The objective function (3.6) minimizes the sum of fixed cost of locating distribution centers, inbound and outbound transportation costs, safety stock costs and the joint ordering and average inventory costs. The first term in the objective function represents the annualized fixed cost of locating distribution centers. The second and third terms represent the variable shipment costs of transporting the items from the distribution centers to the retailers, and from the supplier to the distribution centers, respectively. The fourth term in the objective function represents the cost of safety stock inventory held at the distribution centers to maintain a fill rate of α_k for item k. Finally, the last term represents the joint ordering and average inventory costs. This includes the fixed cost of placing an order at the DCs from the supplier and cost of holding inventory at the DCs. The joint cost of ordering for multiple items is represented by the inclusion of the conditions on the R_{kj} variable to the model (Equations 3.11 and 3.12). R_{kj} is equal to the sum of major and minor costs for the base item while it is equal to the minor cost only for all the other (nonbase) items.

Constraints are the same as those of a classical uncapacitated fixed charge facility location problem. Constraint (3.7) requires each retailer to be assigned to exactly one DC. Constraint (3.8) prevents a retailer from being assigned to a DC unless it is opened. Finally, constraints (3.9) and (3.10) are standard binary constraints.

The model above (3.6-3.10) is a non-linear integer programming model. Our aim is to make location/allocation decisions simultaneously with inventory decisions by using this model. The first two terms of the objective function and the constraints are structurally identical to those of the uncapacitated fixed charge facility location model. However, the non-linear terms, which represent the safety stock inventory and joint ordering and average inventory costs, increase the difficulty associated with solving this model. Despite the difficulties imposed by the nonlinear inventory costs, Daskin, Coullard and Shen (2002) develop an efficient Lagrangian-based solution procedure for their single-item integrated location/inventory model by further simplifying their model with the assumption that the variance-to-mean ratio of demand at each retailer is the same. In fact, the model formulated above is very similar in structure to the integrated location/inventory model presented by Daskin, Coullard and Shen (2002); however, the joint replenishment policy that is used to represent the inventory costs for multiple items in this study results in some structural differences between the two models. The addition of the implications of the joint replenishment policy in the model brings the requirement of the determination of the base items for each DC to be located. In order to find which item is a base item for a DC, we should evaluate the ratio that is used to find the base items, according to the JRP heuristic explained in section 3.2.2. In order to evaluate this ratio, we need to know the amount of demand assigned to each DC for each type of item, which is dependent on the selected DCs and the assignments of the retailers to these DCs. It would be possible to find the base items endogenously by revising the model with the addition of some binary variables and constraints; however, this would result in a more sophisticated model, which would be very hard to solve.

These complications necessitate the development of a solution algorithm, which allows the evaluation of the joint replenishment policy at the DCs. Some heuristic based solution procedures are used to solve this problem, which is explained in the following chapter.

CHAPTER 4

SOLUTION APPROACH

The difference between the multi-item location/inventory model and the traditional uncapacitated fixed charge facility location model stems from the inclusion of inventory cost terms into the former. The nonlinear terms in the objective function of the non-linear integer programming model that we formulate for the multi-item integrated location/inventory problem increase the difficulty in developing an optimal-seeking approach for this model. One of the difficulties stems from the fact that, the demand that is seen by each DC is a function of the demand at the retailers that will be assigned to that DC. Also, the multi-item inventory policy to be implemented at a DC is dependent on the demand seen at the DC, and therefore on the retailer assignments to the DC. In order to solve the integrated model by taking into account the cost implications of a joint replenishment policy at the DCs, we need to apply the JRP heuristic, and determine the base items at each DC candidate site. The determination of the base items through the JRP heuristic requires us to know the demand covered by each DC for each type of item. Therefore, in order to evaluate the cost terms related to the joint ordering policy, the solution approach should allow for the application of the JRP heuristic to specify the base items at each DC candidate.

As an alternative solution methodology, a sequential approach could be developed to solve the integrated location/inventory model. In this approach, the number and the location of the distribution centers and the retailer assignments could be determined first using a multi-item location/allocation model, without considering the inventory costs. Then the rest of the problem is reduced to finding the optimal joint replenishment inventory policy to be adopted at the distribution centers given the distribution of the demand at the distribution centers. Also, the amount of safety stock inventory to be maintained at the distribution centers could be easily determined. However, this approach does not find a solution in an integrated way and ignores the effect of inventory costs in determining the number and location of distribution centers.

In order to solve this location/allocation model in an integrated way by accounting for the inventory costs, we looked for the solution algorithms that can accommodate the complications caused by the type of the cost function and the structure of our model. In fact, our model is similar in structure to the single-item integrated location/inventory model presented by Daskin, Coullard and Shen (2002). They develop an efficient Lagrangian-based solution procedure, which finds the optimal or near-optimal solutions in reasonable times. However, multi-item characteristic of our problem results in some structural differences between our model and the single-item integrated location/inventory model. The inclusion of the joint replenishment policy to our model brings the requirement of distinguishing the items as the base items and nonbase items for each DC to be located. As explained before, the determination of the base items requires us to know the amount of demand assigned to each DC for each type of item, which is dependent on the located DCs and the assignments of the retailers to these DCs. Since we can not find any exact optimization procedure that allows us to evaluate the joint replenishment policy included in our model, we resort to heuristics and develop two heuristic procedures: *improvement type* and *constructive type* heuristics, which are based on some traditional heuristic algorithms developed for location/allocation problems (Kuehn and Hamburger, 1963; Maranzana, 1964; Teitz and Bart, 1968; Whitaker, 1985). Both of the heuristic approaches can handle the difficulties that our model brings forth. For example, the evaluation of JRP heuristic to find out the base items becomes possible by defining a demand coverage area around each distribution center candidate; that is, by forming clusters. The heuristics will be explained in the following sections in detail.

4.1. Improvement Type Algorithm

Improvement type heuristic algorithms generally start with a feasible solution and iterate to obtain a better solution. Our improvement type algorithm has some similarities with the neighborhood search algorithm developed for the classical p-median problem by Maranzana (1964). In that neighborhood search algorithm, any feasible solution or specifically a set of p facility sites is chosen and the demand nodes are assigned to their nearest facility. Set of nodes assigned to a facility forms a cluster around that facility. Then, 1-median problem is solved optimally within each cluster by enumeration. Afterwards the procedure is iterated with the new location of the facilities and clusters until no more changes in the assignments occur.

Our improvement type algorithm starts with a feasible solution in which a number of distribution centers are located and retailers are assigned to these distribution centers. Each distribution center with the retailers assigned to itself form a cluster.

Initial clusters are obtained using two methods in our improvement type algorithm. One of them is solving a p-median problem for the overall network. Then the facilities located by the p-median problem and the retailers assigned to the located facilities form p clusters. In this way, the initial clusters are formed considering only the transportation costs between the distribution centers and the retailers and ignoring the other costs. Since the initial allocation, obtained by p-median solution, defines the amount and the composition of the demand covered at each of the p clusters, the inventory costs under the joint replenishment policy and all other costs can be easily computed for a distribution center to be located in a specific cluster. Then, a single facility location/inventory problem is solved in each cluster by enumerating for all the candidates of distribution centers in the cluster. The solution given by the single facility location/inventory problem is expected to be different from the initial one obtained by the p-median problem, since the former considers all logistics costs while the latter accounts for only the outbound transportation costs.

The other method that is used to initialize the algorithm is using a series of randomly generated set of clusters. The solution procedure followed after the generation of the initial clusters is the same for the randomly generated clusters as in the cluster formation by the *p*-median problem. The only difference between using the *p*-median solution and random clusters is that the overall algorithm is run only once when it is initialized by using the clusters generated by the *p*-median problem. On the other hand, using the randomized set of clusters requires the algorithm to be applied for each random set, and the best objective function value obtained by any of these initial random clusters is selected as the solution.

After forming the initial clusters and then solving a single facility inventory/location problem in each cluster, a series of improvement procedures, namely remove and exchange procedures, are implemented to improve on this initial solution. By using these procedures, the solution is improved by reallocating the retailers to different clusters and updating the solution when an improvement in total cost is obtained. Remove and exchange procedures are implemented until there is no improvement opportunity in total cost. Then, the location of facilities and the retailer assignments in each of the *p* clusters that result in minimum cost is determined at the end of these improvement procedures.

Since the number of distribution centers to be located is indeterminate at the beginning in this problem, like in the uncapacitated facility location problem this overall procedure should be implemented for each possible number of facility locations until the best objective function value is achieved. That is, the algorithm starts with forming only one cluster at the beginning and continues by increasing the number of clusters by one at each iteration. The minimum objective function value attained at each iteration is compared to that of the previous iteration, and the algorithm terminates after the iteration when the objective function value starts to increase.

The flowchart of the improvement type algorithm showing the main steps of the algorithm is provided in Figure 4.1.

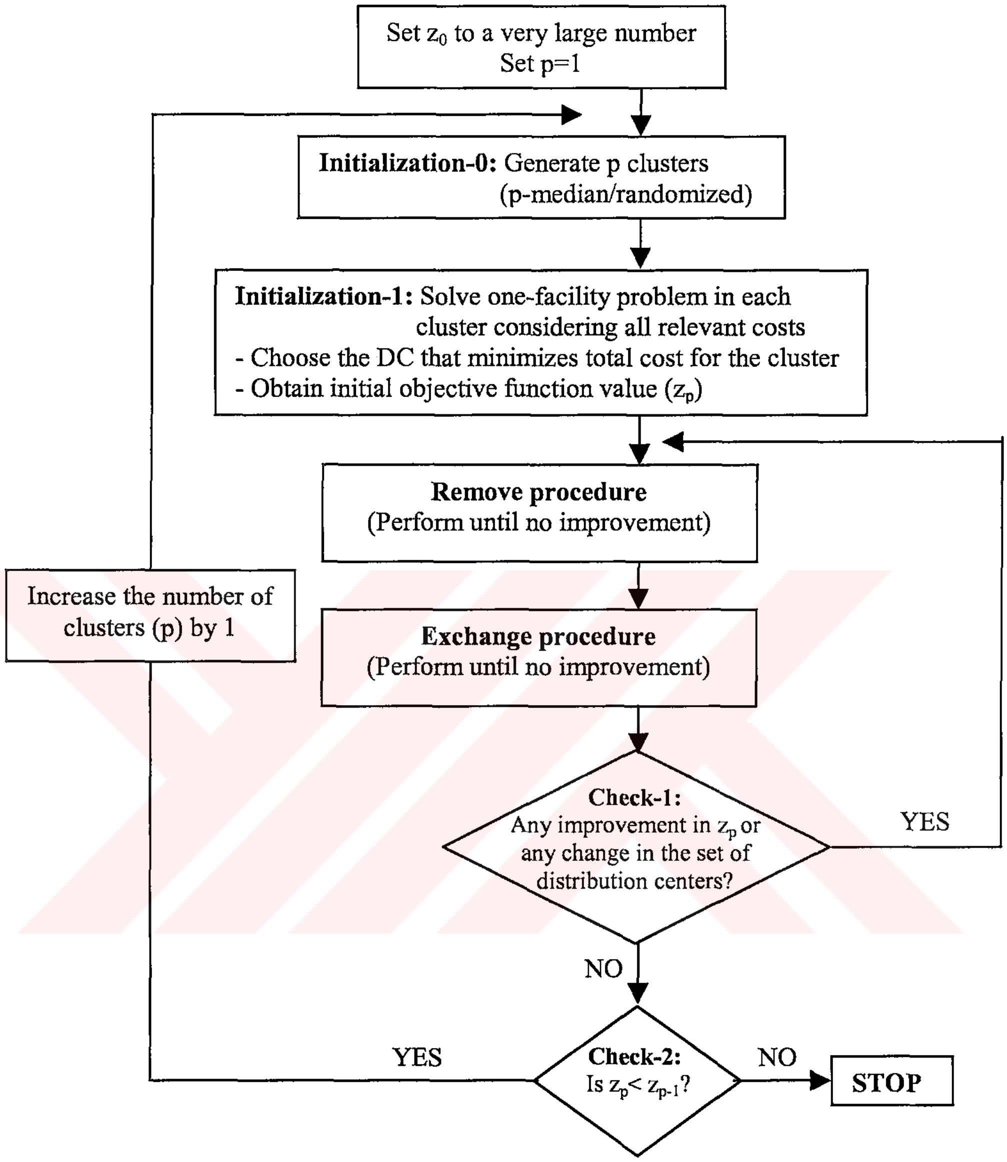

Figure 4.1: Flowchart of the Improvement Type Algorithm

After this introduction for the improvement type algorithm, the main steps of the algorithm will be explained in detail below:

Step 0.

The number of clusters (p) is set to 1 and the objective function value, z_{p-1}, is set to a very large number at the beginning of the algorithm.

Step 1. (Initialization-0)

Any p locations among retailers are chosen as distribution centers. Each distribution center located and the retailers assigned to it form a cluster. As mentioned before, the clusters are generated using two different methods:

- ***Generating a set of random clusters***: In this case, p clusters are generated randomly by assigning each retailer in the system to one of the p clusters arbitrarily. For a certain p, one can choose the number of different random cluster sets to be generated in the algorithm by considering the tradeoff between the solution quality and the computation time. Since the improvement algorithm should be implemented for each of the random set of clusters, the solution time increases as the number of different random sets generated is increased. However, it can be expected that the chance of achieving a better solution increases when the algorithm is applied to as many different random configurations as possible.

- ***Solving a p-median problem:*** In this clustering method, the network is divided into p clusters by solving the traditional p-median problem. The p-median problem minimizes the sum of demand-weighted transportation costs incurred between the distribution centers and the retailers. While solving the p-median problem, we assume that the unit transportation cost does not depend on the type of the item, and the demand for all items at each retailer is expressed in terms of a unit such as kilograms or liters in order to adapt the p-median problem to our multi-item environment.

Figure 4.2 shows an illustration for the configuration of a clustered network for p=5.

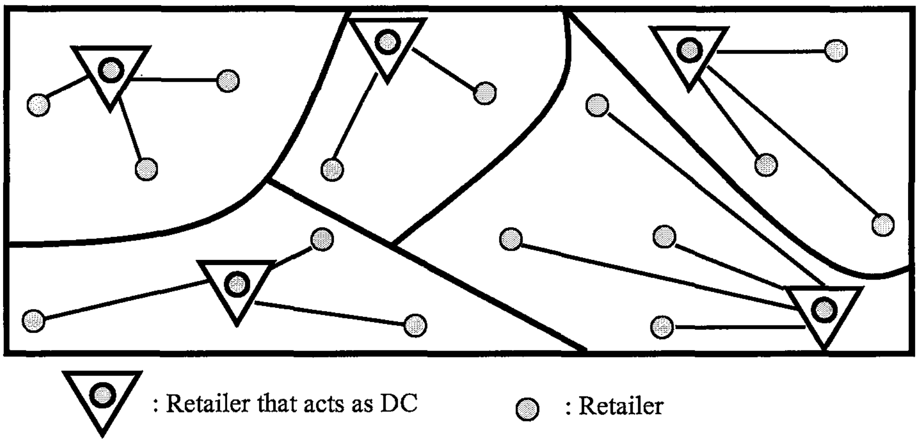

Figure 4.2: An example for clustering of retailers for *p*=5

Step 2. (Initialization-1)

As explained in the previous step of the algorithm, one way of obtaining p initial clusters is solving a p-median problem, which considers only the transportation costs between DCs and retailers. However, our model also includes some additional costs: safety stock, joint ordering and average inventory costs, and inbound transportation costs. When the clusters are generated randomly, on the other hand, cost terms, even the outbound transportation costs, are not taken into account.

In step 2, first, we solve a single facility multi-item integrated inventory/location problem in each cluster, which considers all cost components. Since only one distribution center is to be located in each cluster, the solution is obtained by enumeration. That is, a distribution center is located at each candidate retailer site one at a time, and all other retailers in the cluster are assigned to that distribution center. Since the total amount of demand for each type of item is known and fixed for each cluster, the ratio that is used to find the base item can be evaluated at each candidate facility location. After computing the total cost incurred at each cluster for each distribution center candidate, the candidate that gives the minimum cost is selected as the distribution center of the corresponding cluster. The sum of the costs incurred at each cluster gives us the initial objective function value (z_p). The detailed flow chart for Step 2 is provided in Figure 4.3.

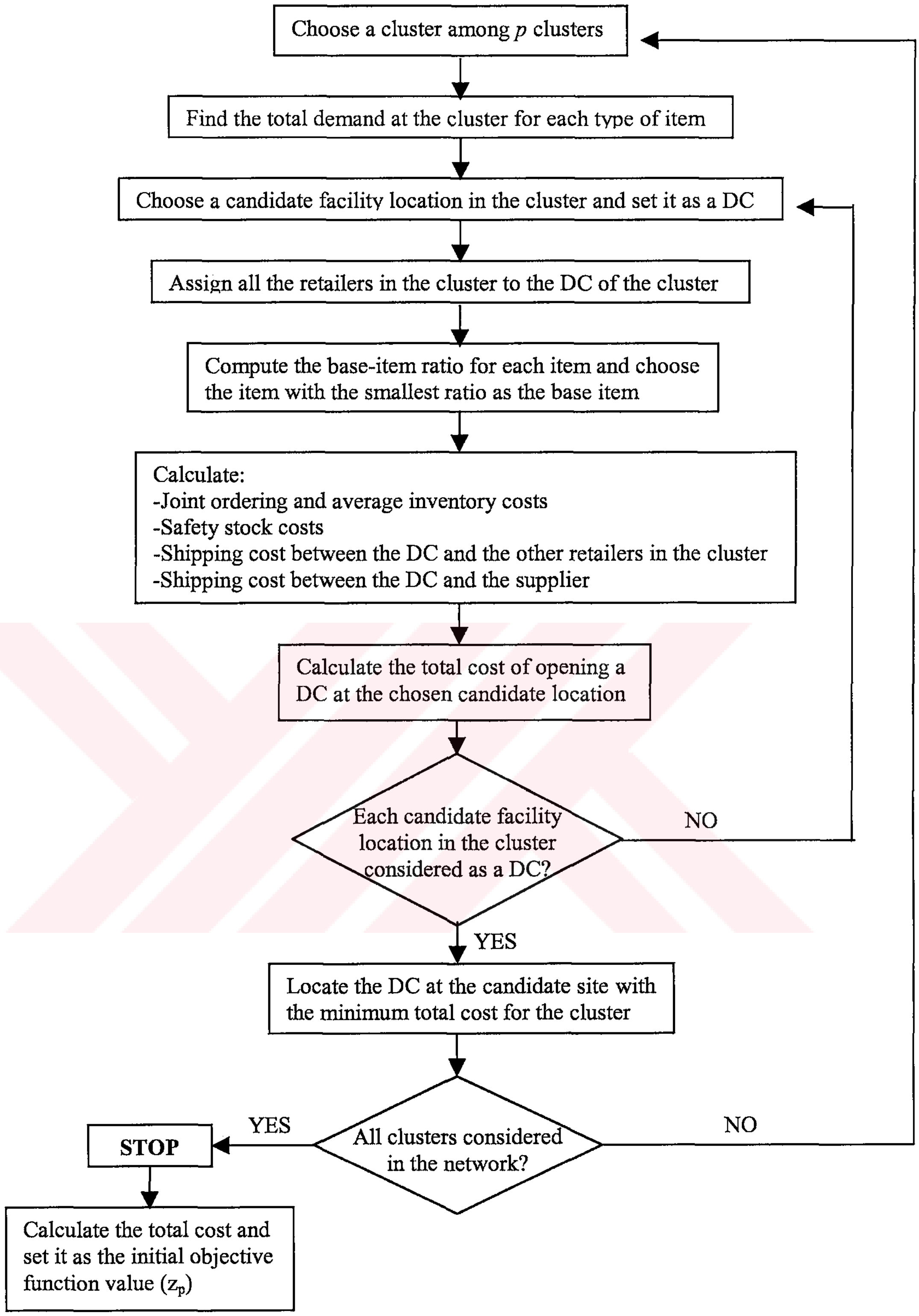

Figure 4.3: Flowchart of the 2nd Step of the Improvement Algorithm

Step 3. Remove Procedure

After obtaining the initial feasible solution and the objective function value for the integrated location/inventory problem, the algorithm then follows a series of improvement procedures. With the facility locations and their respective clusters obtained in the previous step, the algorithm first carries out a removal procedure.

The removal procedure considers the removal of one retailer from one cluster and addition of it to another cluster. Different ways of implementation (strategies) can be applied for the removal procedure while determining the order of retailers to be considered for removal and the order of clusters to be evaluated for the addition of that removed retailer. In this algorithm, the clusters are considered sequentially for the removal of a retailer, and the retailer is added to a new cluster at the first instance when an improvement opportunity in the objective function is obtained. That is, a *'first improvement strategy'* is applied in the remove procedure. The process is carried out for every retailer in all the clusters until there is no room for improvement in the objective function value by the reallocation of the retailers among the clusters.

A new iteration for the removal procedure starts by considering the first cluster of the network for the removal of its elements (retailers). Then a retailer is chosen and removed from the cluster. Since the total cost of the cluster and the location of the distribution center may change with the removal of the retailer, the single facility location/inventory problem is solved for the cluster, and then both the total cost and the location of the distribution center are updated. Then another cluster is considered for the addition of the removed retailer and the retailer is assigned to the new cluster. The single facility location/inventory problem is also solved at this new cluster to account for the possible changes that can occur due to the addition of the new retailer. Then the change in the objective function value due to the reassignment of the retailer is calculated. If there is an improvement in the objective function value, the reassignment of the retailer is realized and the process continues on this improved solution. Otherwise, the reassignment of the retailer is not performed and the retailer remains in the cluster it was assigned to at the beginning of the iteration.

This procedure continues until all the retailers in the cluster are considered for removal. After all the retailers in a cluster are evaluated for an improvement, the next cluster in the network is considered for the removal of its elements. The algorithm does not allow the removal of all the retailers of a cluster; that is, the removals are performed subject to the constraint that each distribution center serves at least its own local demand so that p distribution centers are maintained in the solution. At the end of the first iteration, when all the clusters are evaluated for removal of their elements, it is checked whether any change has occurred during the last iteration in terms of the locations of the distribution centers at each cluster or the objective function value. If one of these changes has occurred with respect to the previous iteration, the algorithm starts a new iteration by considering the first cluster in the network again for removal of its elements. If nothing has changed compared to the previous iteration, the remove procedure is stopped. Then using the network configuration obtained at the end of the remove procedure, the algorithm follows an exchange procedure. The flowchart for the remove procedure is provided in Figure 4.4.

Step 4. Exchange Procedure

In the exchange procedure, each retailer in each cluster is considered for an exchange with a retailer located in a different cluster. The exchange of the retailers between clusters is realized, if the resultant configuration decreases the objective function value. The strategy followed in the exchange procedure is the '*best improvement strategy*'. In the best improvement search strategy, all the possible exchanges are evaluated for a particular retailer and the exchange that improves the objective function most is performed. The algorithm continues until there is no improvement opportunity by exchanging elements between clusters.

A new iteration for the exchange procedure starts with the first cluster of the network for the exchange of its elements. Then a retailer, which will be considered for an exchange with another retailer, is picked from the cluster. Now, we try to find another retailer in a different cluster whose exchange with this chosen retailer improves the objective function most. In order to find this retailer, we consider all

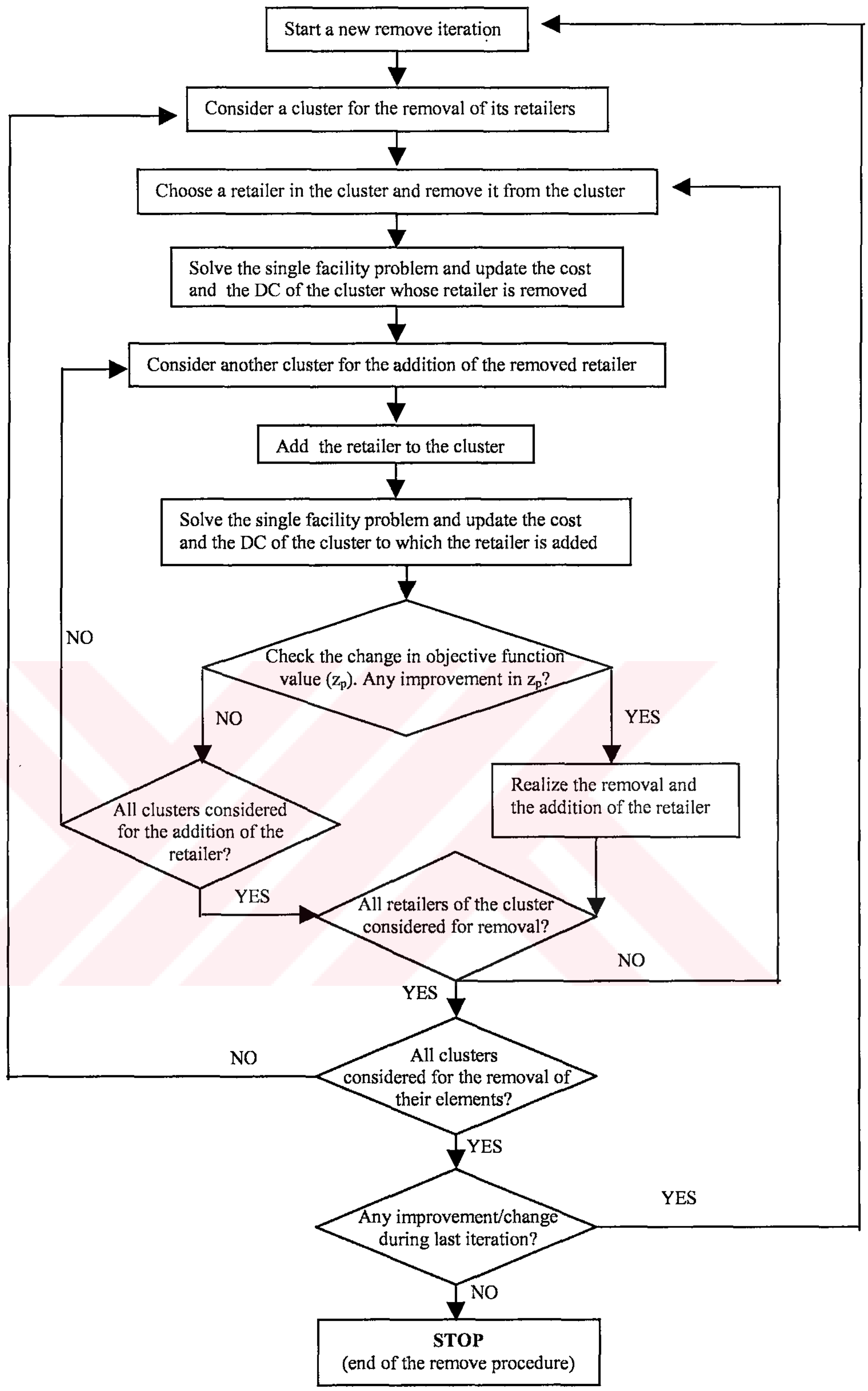

Figure 4.4: Flowchart of the Remove Procedure

the clusters of the network sequentially for the exchange of their elements. After selecting the second cluster, each retailer in this cluster is considered for an exchange with the retailer in the first cluster. While evaluating each of these possible exchanges, the effect of the exchange on the total cost is computed. In order to do that, a single facility location/inventory problem is solved in the clusters whose elements are being exchanged. Then it is checked whether there would be any improvement in the objective function value if the exchange were realized.

The exchange procedure continues in this way by considering every element of all the clusters for an exchange with a particular retailer and calculating the cost of a possible exchange. After all the possible exchanges for a retailer are evaluated, the exchange, which improves the objective function value most, is realized. If any improvement opportunity in the objective function value can not be recorded for a particular retailer, next retailer in the cluster is considered in turn. When an exchange is realized, the process continues by considering a new retailer on the improved solution. The iteration is terminated when all the retailers have been considered for an exchange. After the iteration is over, the algorithm checks whether there exists any change in the network configuration or the objective function value with respect to the previous iteration. If one of these changes has occurred, another exchange iteration is started; otherwise, the exchange procedure is terminated.

The remove and the exchange procedures are iterated in our improvement type algorithm. That is, if any exchange is realized during the exchange procedure, the algorithm applies the remove procedure again to improve the objective function further.

The flow chart of the exchange procedure is provided in Figure 4.5.

Step 5.

After the remove and exchange procedures are implemented, the improved objective function value for the *p* clusters (z_p) is obtained. This minimum objective function value attained is then compared to that of the previous iteration (z_{p-1}). If z_p is greater

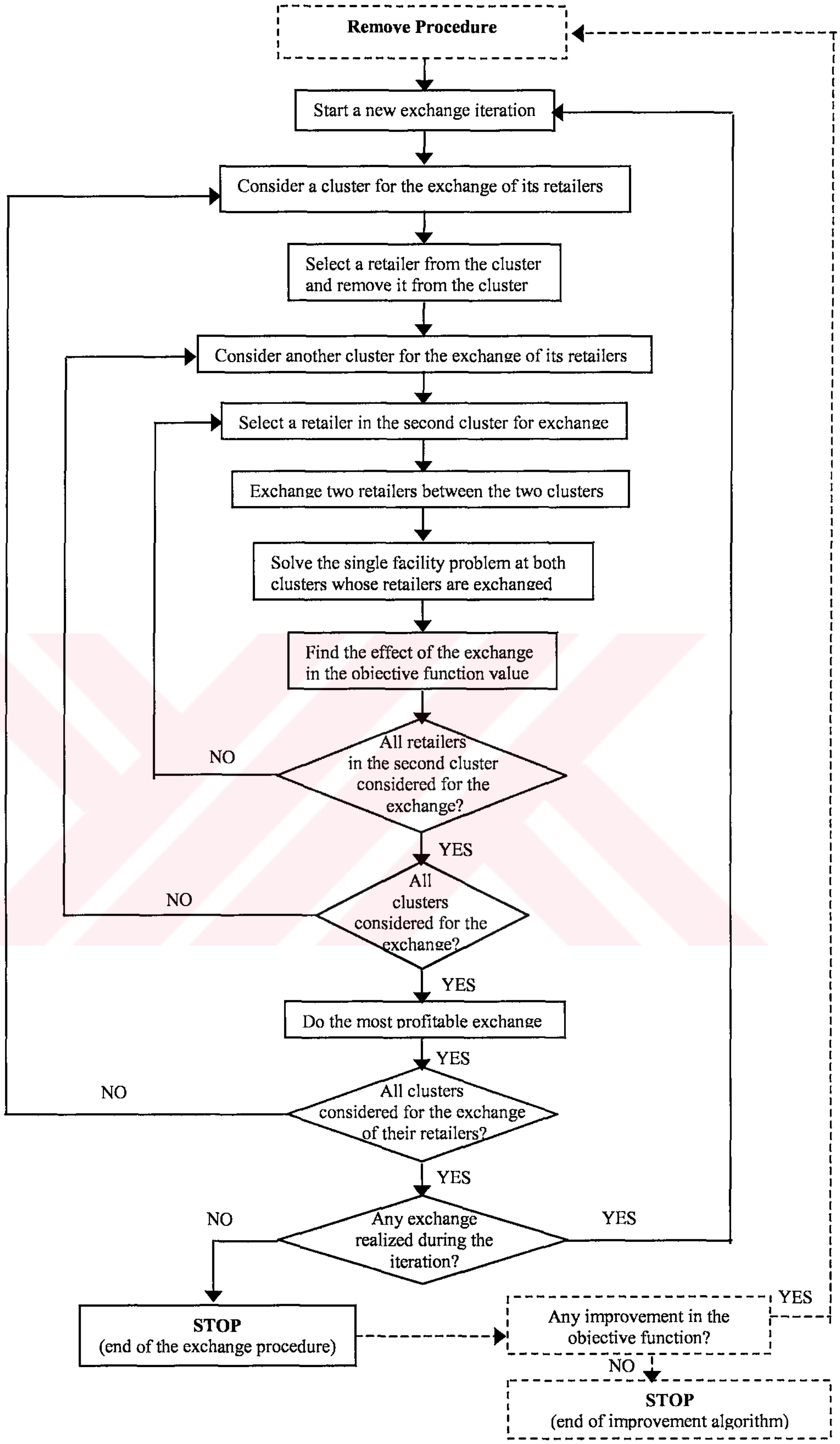

Figure 4.5: Flowchart of the Exchange Procedure

than z_{p-1}, the algorithm is terminated, since this means that opening one more distribution center increases the total cost of the distribution system. If we obtain a smaller objective function value, the algorithm proceeds with a new iteration by increasing the number of distribution centers (clusters) by one. Note that, if the algorithm is initiated with the method of generating random set of clusters, the new iteration starts after the improvement procedures are applied to all the initial random clusters. That is, the objective function value for a particular *p* number of clusters is obtained by implementing the algorithm (Step2 - Step 4) for each random cluster set, and choosing the one that gives the best objective function value.

4.2. Constructive Type Algorithm

The constructive type algorithm that we develop to solve our problem takes its basic idea from the heuristics developed for the location/allocation problems with nonlinear warehousing costs. Although the range of previous work on location-related problems is quite extensive, comparatively less attention has been paid to warehouse location problems in which nonlinear warehousing costs are a significant determinant of optimal warehousing configurations (Whitaker, 1985). Some of the authors who propose heuristic procedures for solving warehouse location problems with non-linear costs are Kuehn and Hamburger (1963), Feldman, Lehrer and Ray (1966), Kelly and Khumwala (1974), and Whitaker (1985). These studies all assume that the warehousing cost function is concave in the warehouse throughput; that is, they use cost structures where the transportation rates and the marginal cost of operating a warehouse decrease as the quantity of goods handled by the warehouse increases. The heuristic type algorithms developed in these studies are said to accommodate any type of warehouse operating function, but computational experiments are reported on the problems where these costs are non-linear and continuously concave over the range of warehouse sizes. Heuristic techniques can generate near optimal solutions to large-scale warehouse location problems having continuous concave warehousing cost functions (Feldman, Lehrer and Ray, 1966).

In the problems with the concave warehousing costs, the trade-off is between the warehouse operating costs and the transportation costs. Because big warehouses are more efficient than small ones, total warehousing costs rise as the number of warehouses is increased. Since shipping costs fall as the number of warehouses is increased, the problem of minimizing total cost is to find the balance between warehouse costs and transportation costs (Feldman, Lehrer and Ray, 1966). The same trade-off exists in our problem; we are trying to find the optimal balance between the transportation costs and the inventory and facility location costs. The analysis of a variety of inventory policies suggests that inventory costs are also generally approximately concave in demand (e.g., the basic EOQ model) or throughput (Schwarz, 1981). Therefore, we can say that our problem is similar in structure to the problems in the literature that include nonlinear warehousing operating costs in their models.

Another characteristic of concave facility costs in location/allocation problems is that, in the absence of constraints on capacity, the optimal allocation for fixed locations is an extreme point. This implies that in a distribution setting all demand in a given location should be served by a single source of supply (Feldman, Lehrer and Ray, 1966). In our integrated location/inventory model, we also assume the existence of the single source constraints such that a retailer should be entirely serviced by one and only one distribution center.

The constructive type algorithm we develop to solve our problem shows similarities with the efficient heuristics developed for the location/allocation problems with nonlinear concave costs. We are particularly inspired by the algorithm developed for the non-linear warehouse location problem by Whitaker (1985), which solved 27 of the 48 problems with lower objective function values than those with the branch and bound algorithm of Khumwala and Kelly (1974). Moreover, the solutions reported for the remaining 21 problems were not worse off than the branch and bound algorithm's optimal solution values. Although the algorithm of Whitaker (1985) is stated to be flexible with respect to the kind of warehousing cost function allowed and can accommodate widely varying cost structures and parameters among the different warehouse sites, the problems with more complex structures may cause the same algorithm to terminate at some distant local minimum point in the total cost curve. The location model in Whitaker (1985) has only one non-linear cost term objective function. Our multi-item integrated location/inventory model can be considered as more complex than that of the Whitaker (1985), since it has two non-linear cost terms in the objective function. Therefore, we adopt a similar algorithm but at the same time we implement different strategies at various levels to increase the algorithm's performance.

Our constructive type heuristic algorithm builds a solution from scratch by locating distribution centers one at a time until the cost of adding one more distribution center increases the total cost of the system. The algorithm starts with zero open facilities, and it adds one more facility to the solution set at each iteration. At the beginning of the algorithm, a single facility location/inventory problem is solved for the overall network by calculating the total cost of locating a distribution center at each candidate location and assigning all the retailers to that particular candidate, that is, by using enumeration. Then the first distribution center is located in such a way as to minimize the total distribution costs. In this way, the solution and the objective function value (z_1) for 1-cluster network are obtained. Afterwards the algorithm proceeds by adding the second distribution center to the solution set. In order to find the second facility whose addition to the solution set reduces the total costs most, we have to evaluate each candidate location that is not currently in solution. After this evaluation, the distribution center whose addition to the solution set results in the lowest cost solution is chosen as the second site, thereby incrementing the number of clusters and facilities (p) by one. After adding a new distribution center to the open set and increasing the number of clusters by one, a series of improvement procedures is implemented on the solution, namely reallocation and interchange procedures, to improve on the initial solution set obtained. Briefly, the reallocation procedure evaluates the total cost impact of removing a retailer node from the distribution center to which it is already assigned and transferring that retailer's demand to another open distribution center. The reallocation procedure has the same objective as the remove procedure in the improvement type algorithm, but the algorithm proceeds in a different manner, which will be explained in detail later. After the reallocation procedure is terminated, the interchange procedure is implemented. At each iteration of the interchange procedure, a distribution center candidate not currently in solution is added to the open set, replacing a member of that set. The interchange procedure used in our algorithm is not a simple pairwise exchange in which unopened distribution center sites are systematically switched with opened facilities, as described by Teitz and Bart (1968). During the course of interchange iteration, there may be multiple additions to and deletions from the open set.

The reallocation and interchange procedures are iterated after the addition of a new distribution center until there is no chance of improvement in the objective function value. Then the improved objective function value attained for *p* clusters, (z_p), is compared to the one obtained in the previous iteration, (z_{p-1}). If z_p exceeds z_{p-1}, the algorithm is terminated. Otherwise, the algorithm starts a new iteration by increasing the value of *p* by one.

There are two main differences between our constructive type algorithm and the algorithm described by Whitaker (1985) for the non-linear warehouse location problem. For a particular *p* number of clusters, Whitaker (1985) applies only the reallocation procedure to improve the initial solution. Then after solving a series of problems for the increasing value of *p* until the point where the total cost is started to increase, he applies the interchange procedure to a range of solutions around this point. In our algorithm, on the other hand, the interchange procedure is applied systematically to each increasing value of *p* throughout the whole range of possible median problems. Other difference between the two algorithms is related to the search strategies used in the reallocation procedure. We use the 'best improvement strategy' instead of the 'first improvement strategy' that is used by Whitaker (1985).

The flowchart showing the main steps of the constructive type algorithm is provided in Figure 4.6.

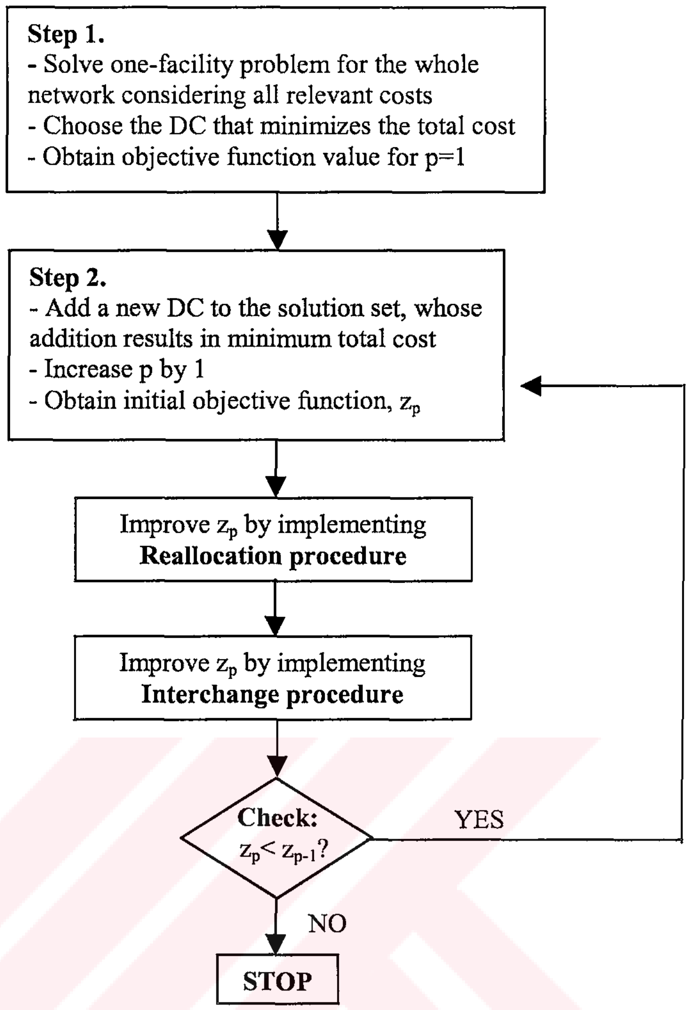

Figure 4.6: Flowchart of the Constructive Type Algorithm

The main steps of the algorithm are explained in detail below:

Step 1.

The algorithm is initialized by solving a single facility location/inventory problem for the whole network. Each candidate facility is considered as a distribution center one at a time, and all the retailers in the network are assigned to that candidate facility. Then the cost implied by each of these configurations is calculated. The initial distribution center chosen is the one that minimizes total logistics costs on the network, which include transportation costs, fixed costs, safety stock inventory costs, and the joint ordering and average inventory costs. In this way, we obtain the objective function value for having one distribution center in the system, z_p.

Step 2.

In this step, the number of distribution centers (*p*) is incremented by one. The distribution center to be added to the solution set is determined by executing the following steps. Each candidate distribution center site, which is not currently in the solution set, is considered in turn. Retailer demands are reassigned to the candidate site from some member of the current solution set if closer on the basis of outbound transportation costs alone and this reassignment process defines a demand coverage area (cluster) of each distribution center. Therefore, total distribution costs, including transportation, fixed, and inventory costs, can be computed in a cluster. This step is repeated for each candidate facility location, and the facility whose addition to the set results in the lowest total cost solution is initially chosen as the new site.

Step 3. Reallocation Procedure

This step attempts a further allocation of customers among the open distribution centers set. The clustering performed in the previous step of the algorithm is based only on the outbound transportation costs. The reallocation mechanism tries to improve the initial objective function value by evaluating the total cost impact of removing each retailer from the facility to which it is already assigned and transferring that retailer's demand to one of the other open facilities. 'Best improvement strategy' is followed in the reallocation of the retailers. That is, the reassignment, which reduces the objective function most, is realized for a particular retailer after all the possible reassignments are evaluated.

The reallocation procedure is composed of two sub-steps, which iterate to improve the objective function:

Step 3.1. The reallocation procedure starts with selecting the first cluster of the network for the removal of its elements. Then a retailer is chosen and removed from its cluster. Afterwards another cluster is considered for the addition of the removed retailer and the retailer is assigned to the distribution center located at this cluster. In order to find the effect of the reallocation of the retailer from one cluster to the other on the objective function value, the cost at both of the clusters is recalculated. This process is repeated by considering the reassignment of the retailer to all the clusters in the network and computing the effect of each reallocation. Then, the most profitable reassignment is realized for the retailer and the process continues on the improved solution by considering a new retailer for reallocation. After all the retailers in a cluster are evaluated for the reallocation process, the next cluster is considered in turn. This step is cycled until no further reassignments are possible, by ensuring that each facility serves at least its own demand so that *p* facilities are maintained in solution.

Step 3.2. The set of distribution centers located in each cluster is not changed during the process explained in Step 3.1. However, since the content of a cluster changes with the reassignment of retailers among clusters, the distribution center of each cluster may also change. In this step, the open facility for each cluster is updated to take the effect of the new configuration of the clusters into account. A single facility location/inventory problem is solved in each cluster and the candidate facility, which minimizes the total cost in a cluster, is chosen as the distribution center. If there is any change in the open facility set, the algorithm returns to Step 3.1 to evaluate further possible adjustments to the current assignment of the retailers.

Steps 3.1 and 3.2 are cycled through to a stable solution, which terminates the reallocation procedure. Figure 4.7 illustrates the reallocation procedure in detail. The algorithm proceeds by applying the interchange procedure to improve on the objective function value (z_p) obtained after the reallocation procedure.

Step 4. Interchange Procedure

In the interchange procedure, each candidate site, which is not in the solution set, replaces a distribution center, which is in the open set at the end of the reallocation procedure. As stated before, the interchange procedure in this algorithm

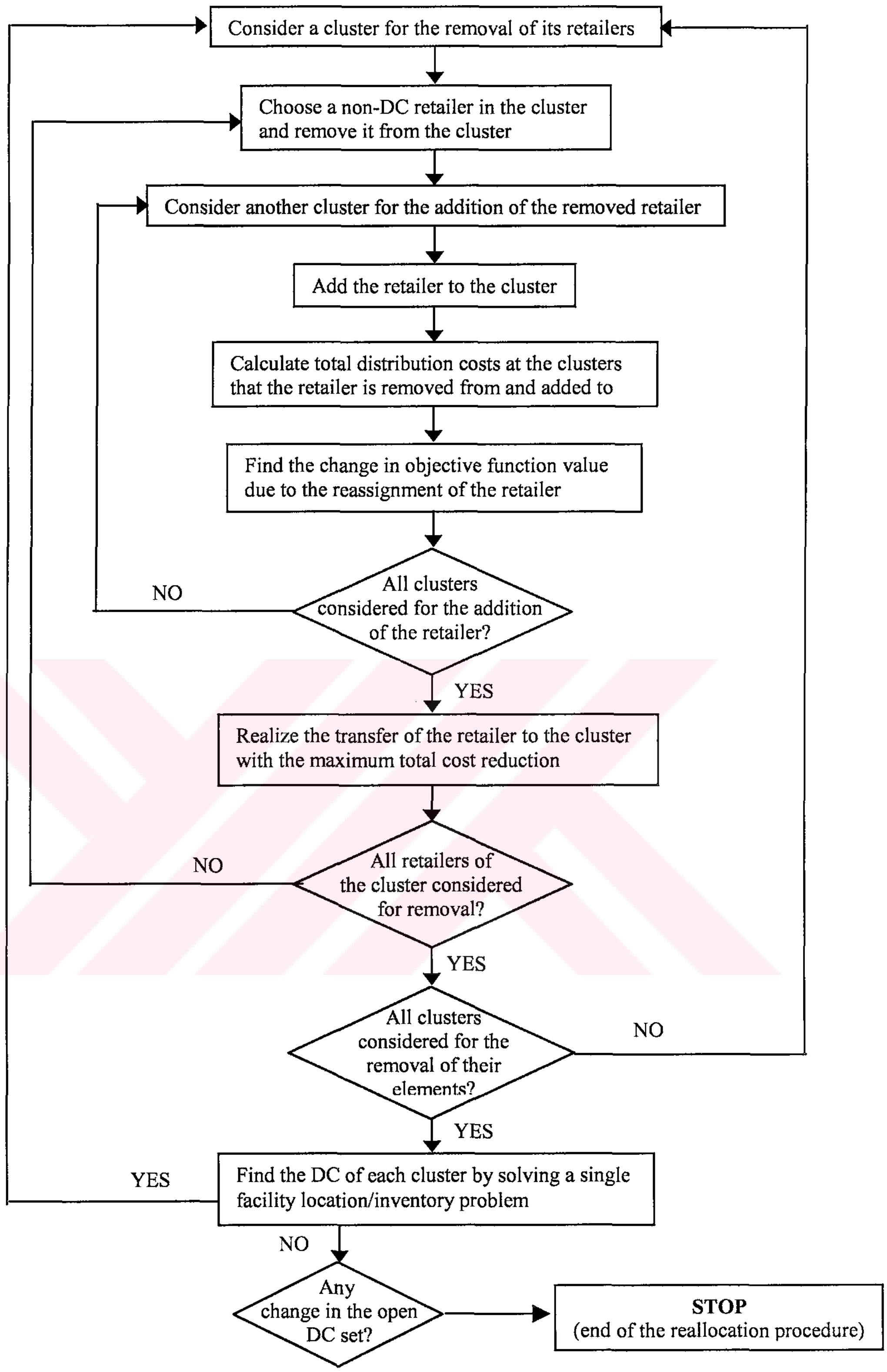

Figure 4.7: The Flowchart of the Reallocation Procedure

does not proceed by interchanging the closed and open facilities after checking the effect of their exchange on the objective function, one at a time. During the algorithm, there may be multiple additions to and deletions from the open distribution center set.

Each iteration of the interchange procedure aims to find the best removal of a distribution center from the solution set, when the distribution center to be added to the set is known. The following steps are implemented at each iteration of the interchange procedure:

Step 4.1. An iteration of the interchange procedure starts with the addition of a candidate location, call it k, which is not currently in the solution, to the open distribution center set. Then the retailer nodes are reassigned to the distribution center k from distribution centers, if they are closer to site k on the basis of outbound transportation costs alone. In this way, the number of distribution centers (clusters) in the network is increased to $p+1$. Since we know the amount and composition of demand at each cluster after forming the clusters, we can calculate the sum of the distribution costs at each cluster. Then, the initial objective function value for locating $(p+1)$ distribution centers is obtained.

Step 4.2. The reallocation procedure, explained in Step 3, is implemented in this part of the interchange algorithm. That is, a test for possible nodal reallocations among distribution centers in the open set is conducted, considering the total cost impact of reassigning retailer demands (Step 3.1). Afterwards, the distribution center of each cluster is updated to take the effect of the retailer assignments (Step 3.2). As before in the reallocation procedure, these two steps are cycled to a stable solution, except that an additional constraint is added preventing the distribution center k from dropping from solution, and maintaining it at all times as the facility of cluster k. For cluster k, we only update the distribution cost due to the retailer reassignments by fixing the open facility of this cluster.

Step 4.3. Since there are (p+1) distribution centers in the open set, one cluster must be eliminated and its retailers are distributed among the other facilities in solution. For each cluster except cluster k, the sum of the difference in transportation costs between the closest and second closest open distribution center is computed over all the retailers in the cluster. Then the cluster with the minimum such cost is eliminated from the solution, and the both retailers and the distribution center of this cluster are reallocated to the next nearest distribution centers. Afterwards the single facility location/inventory problem is solved in each of the p clusters remaining in the solution, including cluster k, and the distribution center located in each cluster is updated.

Step 4.4. For p clusters and their corresponding distribution centers, the reallocation procedure is reapplied. This step proceeds in the same way as Step 4.2 does, except that the constraint on maintaining distribution center k as the open facility for cluster k is relaxed in this step.

Step 4.5. In this step, the total distribution cost for the new configuration is compared to the current solution value, and if it is less, this open facility set of the new configuration becomes the new distribution center set. Steps 4.1-4.4 constitute an interchange iteration, and these steps are cycled through for each distribution center candidate. If we assume that there are m retailers in the distribution network, which are all distribution center candidates, the interchange algorithm is terminated after (m-p) iterations have been completed consecutively without improvement to the solution value. Figure 4.8 represents the flow of the interchange procedure.

We provide the computational results obtained by these algorithms for the multi-item integrated location/inventory model in the following chapter.

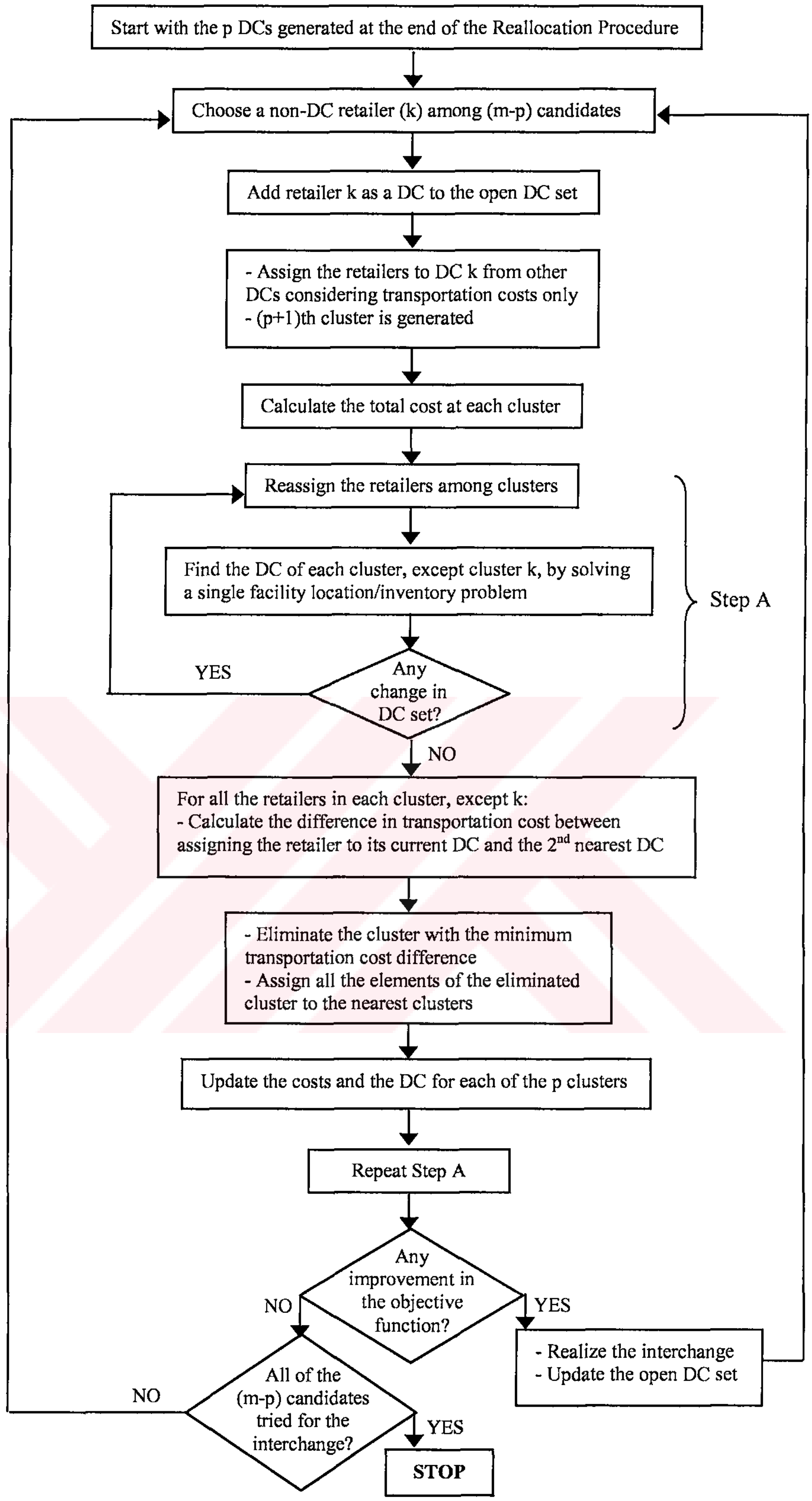

Figure 4.8: The Flowchart of the Interchange Procedure

CHAPTER 5

COMPUTATIONAL RESULTS

In this chapter, we analyze our multi-item joint location/inventory model further by performing some computations on the problem instances generated. In §5.1, we introduce the data set we use in the computational experiments and explain how the necessary parameters of the problem are generated. Then, in §5.2, the computational results obtained by implementing the improvement and constructive type heuristics on the generated problem are given and analyzed in detail. Also, we compare the results obtained by these heuristics and examine their performances for different cases. Finally, the results of the sensitivity analysis performed to investigate the effects of inventory and shipping costs, joint order cost, and demand variance on the results are presented in §5.3.

5.1. The Data Set

We test the heuristic algorithms developed to solve the multi-item integrated location/inventory model for several problem instances obtained with the data set we generate. While generating the data related to the problem instance that is used in the computational testings, we try to do our best to reflect relatively more realistic conditions. However, there are many parameters in our model that are difficult to estimate without analyzing actual corporate data; for this reason, we have also examined the data sets used by similar studies and checked the relations among the various parameters used in their data sets in order to avoid the inconsistencies among different parameters at least. Also, the sensitivity analysis performed on a variety of cost parameters may compensate for the errors of estimation for these parameters and provide alternative solutions to account for the changes in parameters.

For the computational experiments, an 81-node network is used where each node represents one of the 81 cities in Turkey. The positions of these cities in Turkey map and their respective codes used through the computations are provided in APPENDIX A. We assume that there is an aggregated retailer (in terms of demand) in each of these 81 cities, each of which is also a candidate distribution center. There is a single supplier that is located in Ankara.

Associated with each of the retailers, random demand is assumed for four different items. The data for demand mean and variation for the items at each retailer are generated using the population data based on the 2000 Turkey census. The mean annual demand for each type of item is obtained by dividing the population of each city by a different constant and rounding the result to the nearest integer, as illustrated in Table 5.1. Also, the demand for each type of item is assumed to occur in kilograms at each demand point (retailer).

Table 5.1: Generation of the Mean Demand at each Retailer for each Type of Item

	Item 1	Item 2	Item 3	Item 4
Mean demand at retailer i	$(\text{Population})_i/1000$	$(\text{Population})_i/1250$	$(\text{Population})_i/1500$	$(\text{Population})_i/2000$

The items are assumed to have different levels of demand variances, which are generated by defining a coefficient of variation (CV) level for each type of item. The coefficient of variation is used to express the variation as a fraction of mean. The CV levels assumed for each item is presented in Table 5.2.

Table 5.2: CV Levels Set for each Item Type

	Item 1	Item 2	Item 3	Item 4
CV ratio (σ/μ)	0.2	0.4	0.4	0.5

We estimate the fixed cost of locating a distribution center in a city based on the value of land in the city. The 81 cities are divided into three groups according to the cost of unit square meter land in these cities. The cost of unit square meter land in each city is approximated by arranging the data, published in *http://www.gelirler.gov.tr* for the declaration of Turkish property tax levels for the year 2002. After arranging these data, three different intervals are determined to estimate the annualized fixed cost of locating a distribution center at each city. Three such intervals for the annualized fixed cost (in dollars) are generated using uniform distribution:

- U[30000, 50000] to represent the nodes with low values of fixed costs,
- U[60000, 90000] to represent the nodes with moderate values of fixed costs, and
- U[100000, 150000] to represent the nodes with high values of fixed costs, rounded to nearest integer values.

Unit shipment costs are assumed to be both item type and distance dependent while formulating our model. However, the unit shipment costs are determined considering only distances between the cities in our computations; that is, transportation costs are not differentiated among the item types. Since the demand for the items is defined in terms of kilograms, unit cost of shipping is obtained by multiplying the distances between the nodes by unit cost of shipping one kilogram of item per one kilometer. For purposes of illustration, shipping rates between the supplier and the distribution centers are evaluated at $0.015 per kilometer per kilogram whereas the sum of the shipping and delay costs from distribution centers to retailers is considered to be $0.03 per kilometer per kilogram. The unit cost of transporting items from distribution centers to retailers is assumed to be larger than that of transporting items from distribution centers to retailers in order to take into account the cost of the shipments that occurs in each city. The distances between the cities are based on the data provided in *http://www.kgm.gov.tr*. The distance matrix used is provided in APPENDIX B.

The lead time from the supplier to each candidate distribution center is determined according to the distance between the two nodes. The lead time is set to 48 hours for distances greater than 600 kilometers, and 24 hours for distances less than 600 kilometers.

The level of major ordering cost is assumed to be different among the distribution center candidates. Major ordering cost at each candidate distribution center location (A_j) is set to a random number drawn from uniform distribution. Also, an amount proportional to the distance between the supplier and the candidate distribution center *j* ($distance_j$) is added to these generated values to account for the fixed part of the shipment cost. The A_j values (in dollars) are obtained by computing U[450, 550] +0.1*($distance_j$) and rounding the result to the nearest integer. Minor cost of ordering item type *k* at a distribution center candidate *j*, (a_{kj}), is also generated using uniform distribution and assumed to be dependent on the values of major ordering cost at a particular candidate. Then, a_{kj} variables are generated by rounding the number given by U[A_j/20, A_j/10] to the nearest integer.

The unit cost (c_k) and unit inventory holding cost (h_k) parameters for the items are provided in Table 5.3.

Table 5.3: Unit Cost and Unit Inventory Holding Cost of the Items (in dollars)

	Item 1	**Item 2**	**Item 3**	**Item 4**
Unit cost of item	83	116	150	200
Unit inventory holding cost	5	7	9	12

The unit cost of an item is assumed to be the same at all the retailers. Inventory holding cost represents all the storage and inventory keeping costs for a particular type of item, and is dependent on the value of the item. It is computed by using the equation $h_k = c_k * I$, and assuming that, the cost in dollars of carrying one dollar of inventory for one year (I) is equal to 0.06. Also, the inventory holding cost is assumed to be identical for all the distribution center candidates for the same type of item.

Lastly, the desired probability of not stocking out at a distribution center, fill rate, is assumed to be identical for each type of item and is set to 0.975. Then the corresponding z_α value for this service level is 1.96.

Marse and Roberts (1983) random number generator is used for the generation of all the random parameters in this problem. Pascal code for this generator is provided by Law and Kelton (1991).

The problem instance that is generated in this section will be referred to as the `base case` from this point on. Other problem instances are obtained by modifying the parameters that are used in the base case.

5.2. Implementation of the Heuristic Algorithms for the Base Case

In order to solve the problem instances created, the improvement and constructive type heuristic algorithms are both coded in Pascal, and computational tests are performed on a Compaq Prosignia computer with a 550 Mhz Pentium III processor and 128MB memory.

5.2.1. The Improvement Type Algorithm

5.2.1.1. Preliminary Results for Initialization

As explained before, the improvement type algorithm is initiated by using the clusters generated using two methods:

- *P-median problem*: The *p*-median problem is solved using SITATION, which is facility location software that accompanies Daskin (1995). Among several solution methods offered by SITATION to solve the *p*-median problem, we choose the Lagrangian relaxation approach as the solution method.
- *Random generation*: Marse and Roberts (1983) random number generator is used for assigning the retailers to *p* clusters arbitrarily, and forming randomized clusters. As stated before, the number of the random cluster sets may affect both computation times and solution quality. Therefore, some preliminary runs are performed in order to decide on the number of random sets to be generated and used in the improvement type algorithm computations to solve the multi-item location/inventory problem.

The initial results obtained for the base case by implementing the improvement type algorithm, which is initialized by using the clusters generated by the *p*-median problem and also randomly, are provided in Table 5.4.

Table 5.4: Some Preliminary Results Obtained by the Improvement Type Algorithm

	clustering by p-median				
p	**initial obj. func.**	**obj. func. (last)**	**rand (50)**	**rand (200)**	**difference(50&200)**
1	3,049,318.525	3,049,318.525	3,049,318.525	3,049,318.525	0.000%
2	2,963,248.887	2,904,335.032	2,878,728.838	2,878,728.838	0.000%
3	2,838,092.511	2,768,547.666	2,752,651.622	2,743,029.411	0.350%
4	2,714,194.855	2,667,121.307	2,639,629.141	2,639,629.141	0.000%
5*	2,675,368.875	**2,553,300.023**	**2,553,300.023**	**2,553,300.023**	0.000%
6	2,678,427.079	2,557,337.551	2,557,337.551	2,557,337.551	0.000%
7	2,676,800.023	2,568,799.707	2,568,799.707	2,568,799.707	0.000%
8	**2,647,764.362**	2,589,165.899	2,590,094.593	2,590,049.878	0.002%
9	2,716,500.417	2,618,814.864	2,614,170.312	2,600,386.504	0.527%
10	2,717,875.663	2,631,232.117	2,632,040.900	2,614,837.160	0.654%
11	2,755,924.438	2,673,692.370	2,641,593.525	2,641,548.810	0.002%
12	2,795,366.582	2,700,332.423	2,674,921.372	2,663,809.727	0.415%
13	2,841,316.718	2,728,642.416	2,695,400.564	2,687,406.591	0.297%
14	2,863,434.727	2,747,583.327	2,730,039.875	2,722,793.928	0.265%
15	2,917,834.425	2,775,176.910	2,752,285.819	2,751,208.598	0.039%

computation time (in seconds)	***25***	***1657***	***6598***

In order to test the algorithm's performance with respect to the sample size of the randomly generated clusters, two different sets consisting of 50 and 200 random initial solutions are used.

The first column of Table 5.4 represents the number of clusters or the number of distribution centers located in the network (*p*). The second column includes the total cost values, which are calculated by using the solutions of the *p*-median problem for each value of *p*. In other words, the values in the second column corresponds to the total logistics costs, if one makes the strategic location/allocation decisions for the base case according to the solutions of the *p*-median problem, which considers only local delivery costs. The objective function values achieved after the implementation of the improvement procedures on the initial solutions of the *p*-median problem are represented in the third column. Finally, the fourth and fifth columns include the minimum objective function values obtained after implementing the improvement procedures to different random initial cluster sets with samples sizes 50 and 200, respectively.

As explained before, the algorithm is designed to terminate at the point where the objective function value starts to increase. According to the results presented in Table 5.4, it is seen that there is an increase in the objective function value when the value of *p* is incremented from 5 to 6. That is, the results obtained for each of the starting solutions suggest that we open 5 DCs with a cost of approximately $2.5 million. Although the algorithm must be terminated after seeing that the objective function starts to increase when the number of DCs is increased to 6, we run the algorithm for the *p* values up to 15. The main reason for the additional runs is to observe the progress of the objective function value after the point it starts to increase, and to be sure that the best objective function value we achieved is the minimum value we can achieve during the course of the algorithm. According to the results presented at the table above, we have not ever come up with a situation in which the objective function value decreases again after attaining the minimum point. We should note that the computation time declared in the table corresponds to time that is recorded at the point where the objective function starts to increase for all three cases.

The preliminary results indicate that using randomized clusters as the initial solution to start the improvement type algorithm gives lower objective function values most of the time when compared to the improved values obtained from *p*-median initial solutions. Also, it is observed that better solutions are obtained as the sample size of the random clusters is increased from 50 to 200. However, the results obtained by running the algorithm with 200 random clusters are better than the results obtained by 50 random clusters at most 0.654%, which has occurred at p=10. Considering the time and quality trade-off, we choose to use 50 randomly generated clusters and *p*-median clusters to initiate the improvement type algorithm for further runs performed in this study.

5.2.1.2. Evaluation of the Results

After determining the number of the random set of clusters to be generated as 50, we apply the improvement type algorithm for the base case. The summary of the results obtained is in Table 5.5. The table includes the objective function values achieved by applying the improvement procedures to the initial feasible solutions obtained by the random and *p*-median clusters as well as the total cost of a *p*-median solution for each value of *p*.

The minimum of the objective function values achieved by applying the improvement algorithm for randomized and *p*-median clusters are highlighted. It is observed that the values obtained by applying the algorithm to randomized clusters are better than the values achieved through *p*-median clusters for 14 of the 15 values of *p*. However, when we examine the solution times, we see that the application of improvement procedures to the *p*-median initial solution resulted in much less time. This is not surprising; since the improvement algorithm is iterated 50 times when it is applied to the randomly generated clusters and the best objective function value ever achieved is selected as the solution. On the other hand, we apply the algorithm only once when we start the algorithm with the clusters obtained by the *p*-median

Table 5.5: The Results of the Improvement Type Algorithm for the Base Case

	p-median						Opened DCs (p median)						Opened DCs (random)						Cost composition (min.of p-med&rand)			
p	initial obj. func.	obj. func. (last)	rand (50)	Impr %	time (p)	time (rand)													shipping	fixed	safety	order+inv
1	3,049,318.525	3,049,318.525	3,049,318.525				6						6						2,866,541.910	135,456.000	10,777.059	36,543.556
2	2,963,248.887	2,904,335.032	2,878,728.838	2.85%	4	326	6	38					6	80					2,629,923.750	184,330.000	13,698.700	50,776.388
3	2,838,092.511	2,768,547.666	2,752,651.622	3.01%	4	355	6	38	54				6	12	54				2,453,955.960	219,138.000	17,976.056	61,581.605
4	2,714,194.855	2,667,121.307	2,639,629.141	2.75%	3	288	2	3	54	71			1	6	12	54			2,256,484.860	291,154.000	19,925.922	72,064.359
5*	2,675,368.875	**2,553,300.023**	**2,553,300.023**	4.56%	12	424	**1**	**3**	**12**	**54**	**71**		**1**	**3**	**12**	**54**	**71**		2,173,224.960	277,024.000	22,290.606	80,760.456
6	2,678,427.079	2,557,337.551	2,557,337.551	4.52%	2	264	1	3	12	28	54	71	1	3	12	28	54	71	2,107,851.810	338,101.000	23,862.269	87,522.472
7	2,676,800.023	2,568,799.707	2,568,799.707	4.03%															2,161,711.110	321,552.000	24,300.215	93,266.631
8	**2,647,764.362**	2,589,165.899	2,590,094.593	2.21%															2,198,651.850	342,106.000	24,381.743	95,606.061
9	2,716,500.417	2,618,814.864	2,614,170.312	3.77%															2,134,547.205	400,676.000	26,139.149	103,159.527
10	2,717,875.663	2,631,232.117	2,632,040.900	3.19%															2,068,672.680	464,424.000	27,349.152	108,670.181
11	2,755,924.438	2,673,692.370	2,641,593.525	4.15%															2,069,105.250	467,421.000	28,516.164	113,459.888
12	2,795,366.582	2,700,332.423	2,674,921.372	4.31%															2,028,666.780	528,122.000	30,272.616	120,987.224
13	2,841,316.718	2,728,642.416	2,695,400.564	5.14%															2,017,010.025	601,605.000	30,058.352	120,809.893
14	2,863,434.727	2,747,583.327	2,730,039.875	4.66%															2,010,809.715	560,921.000	31,742.521	126,566.639
15	2,917,834.425	2,775,176.910	2,752,285.819	5.67%															1,969,667.175	624,521.000	33,595.079	134,874.033

Computation time in seconds (up to the increase in obj.fnc): 25 1657

Overall Improvement with respect to p-median solution (%): 3.57

problem. We should note that, in all the computations we perform, we ignore the minimal amount of time that passes in solving the p-median problem by SITATION and generating randomized clusters.

The minimum objective function values obtained by the improvement algorithm initiated with either randomized or p-median clusters are used to compute the amount of improvement obtained with respect to the initial p-median solution for each value of p. The fifth column of the Table 5.5 represents the amount of improvement in percentages for each p and calculated as follows:

$$\text{Improvement percentage (for p)} = \frac{\begin{pmatrix}\text{obj. func. value of the} \\ \text{p-median solution}\end{pmatrix} - \begin{pmatrix}\text{min. obj. func. value obtained} \\ \text{by the improvement algorithm}\end{pmatrix}}{\begin{pmatrix}\text{obj. func. value of the} \\ \text{p-median solution}\end{pmatrix}}$$

Although most of the results for different values of p generated by different clustering methods are different, the best solution suggested by both methods is identical. That is, the minimum objective function value attained through two different clustering methods for the base case is the same. Both results suggest that we open 5 DCs, namely at Adana (1), Afyon (3), Bingöl (12), Sakarya (54), and Kırıkkale (71). Also, the retailer assignments to the located DCs are the same according to the results of two solutions obtained. As also observed in Table 5.5, for the p values less than 5, the solutions for the p-median and random clusters suggest locating DCs at different locations. Also, the smaller set of opened DCs is not a subset of the set of opened DCs at the best solution according to the results obtained by both of the clustering methods.

The location of the opened DCs and retailer assignments are also represented in Figure 5.1. The retailer assignments to the opened DCs for the base case are summarized in Table 5.6. Also, the percentage of the total demand covered by each facility over all four items can be seen in Table 5.7.

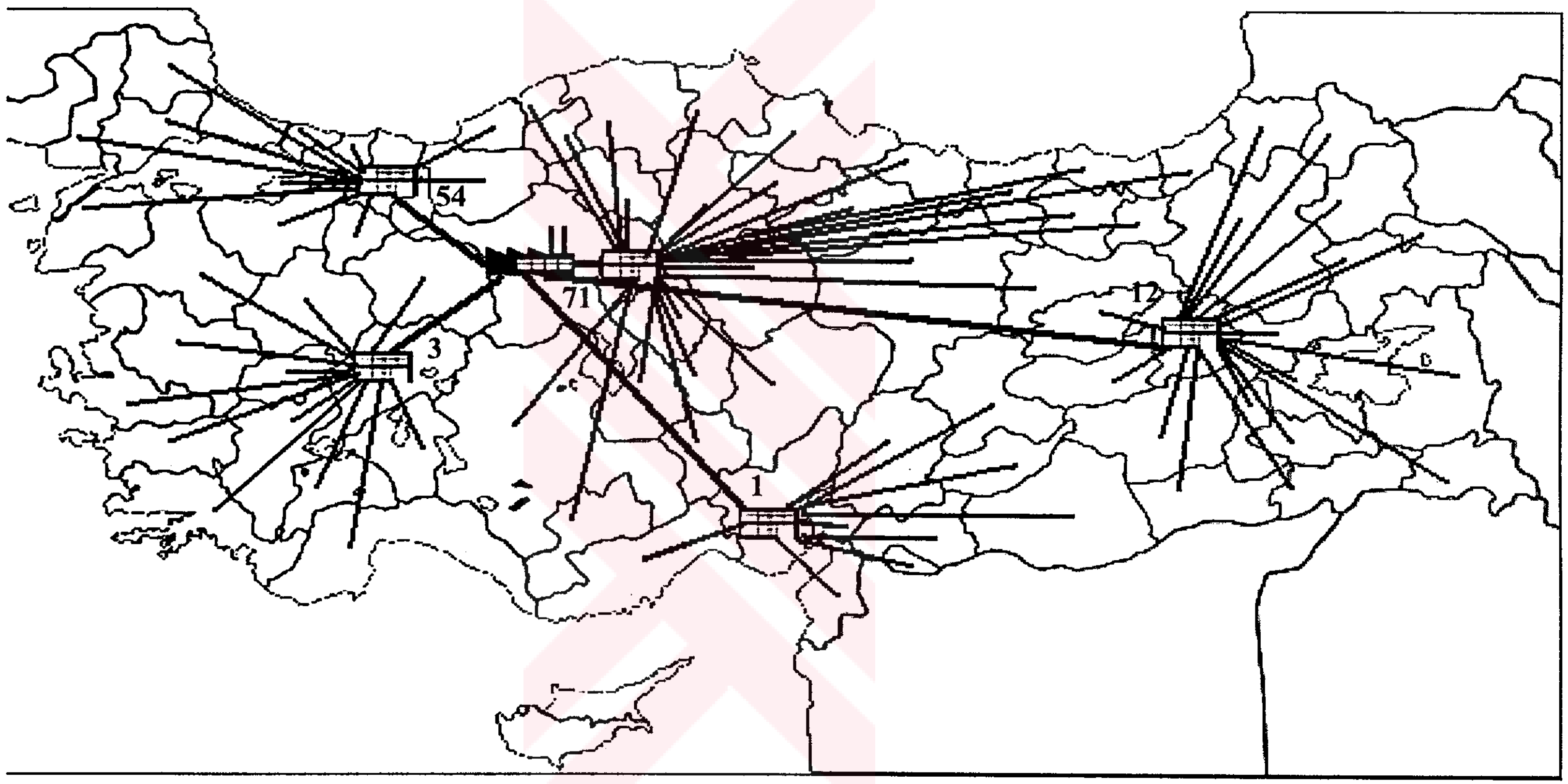

Figure 5.1: Representation of the Solution for the Base Case

Table 5.6: Retailer Assignments for the Base Case

Facility	Assigned Retailers
1	1, 2, 27, 31, 33, 44, 46, 63, 79, 80
3	3, 7, 9, 10, 15, 20, 26, 32, 35, 43, 45, 48, 64
12	4, 8, 12, 13, 21, 23, 25, 30, 36, 47, 49, 56, 62, 65, 72, 73, 75, 76
54	11, 14, 16, 17, 22, 34, 39, 41, 54, 59, 67, 77, 81
71	5, 6, 18, 19, 24, 28, 29, 37, 38, 40, 42, 50, 51, 52, 53, 55, 57, 58, 60, 61, 66, 68, 69, 70, 71, 74, 78

Table 5.7: Percentage Demand Covered by each Facility for the Base Case

Facility	Demand Covered
1	12.59%
3	20.13%
12	13.42%
54	27.85%
71	26.01%

The solution that suggests opening 5 DCs corresponds to the point where the total cost is minimized. When the composition of the costs for each value of p is examined, the trade-off between different cost components can be defined clearly. As observed in Table 5.5 and illustrated in Figure 5.2, as the number of DCs located is increased, the total cost first decreases to some point and then starts to increase. The convexity of the total cost curve is the result of the behaviors of the cost components with respect to the number of DCs located. As we locate more DCs, the outbound transportation costs that occur between the DCs and retailers decrease, while the inbound transportation costs between the supplier and the DCs increase. The shipping cost represented in Table 5.5 and Figure 5.2 is the sum of the outbound and inbound transportation costs. It is observed that when the number of DCs located is increased, the shipping costs decline as long as the decrease in outbound transportation costs is more than the increase in inbound transportation costs. On the other hand, there is an increase in the fixed costs, safety stock costs, and joint ordering and average inventory costs, as the number of DCs located is increased. Opening new DCs implies an increase of inventory costs, since larger total inventory is held at the DCs.

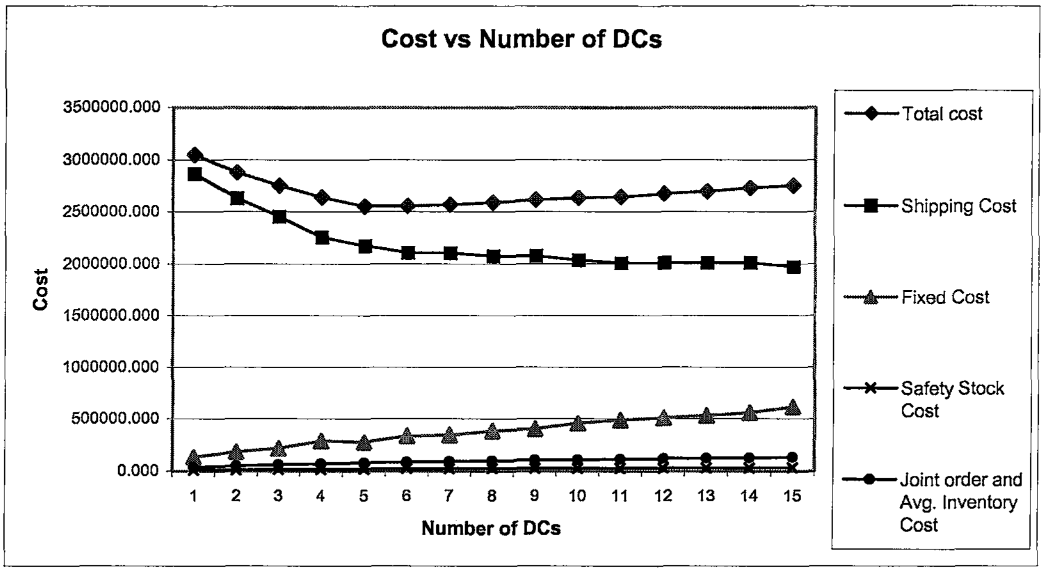

Figure 5.2: Representation of the Costs as a Function of the Number of DCs for the Improvement Type Heuristic

Figure 5.3 breaks down the total cost of approximately $2.5 million, which corresponds to opening 5 DCs for the base case, into its constituent parts. According to the figure, the safety stock inventory and joint ordering and average inventory

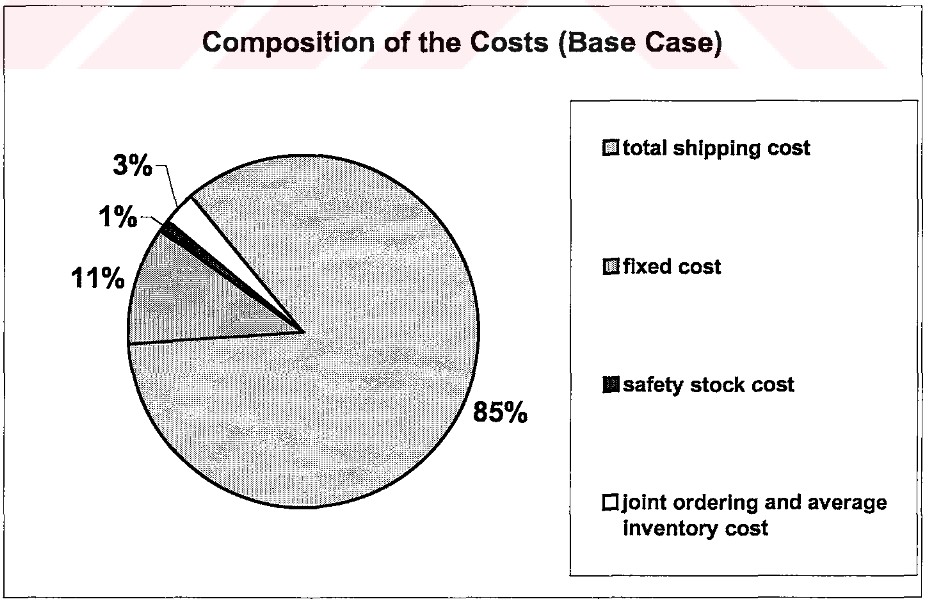

Figure 5.3: Distribution of the Costs for the Base Case

costs constitute 1% and 3% of the total cost, respectively. The larger part of the costs is comprised by the transportation costs and fixed cost of locating distribution centers.

Solving the p-median problem to generate the initial clusters also gives us the chance of comparing the solution of our model with the p-median solution. Comparison of the results of the multi-item integrated location/inventory problem to the total cost implied by the p-median problem justifies the introduction of the additional cost terms in our integrated location/inventory model. The results obtained through p-median solutions suggest opening 8 DCs with a cost of approximately $2.65 million. Then the overall cost improvement we obtain through the improvement procedures is 3.57% for the base case. Also, when the retailer assignments corresponding to the improved solutions are examined, it is seen that it is better to assign some of the retailers to the non-closest DCs. It means that when the inventory costs are taken into account, assignment of the retailers to the closest facility is not always optimal due to the risk pooling effects. For example, 11 of the 81 retailers are assigned to a DC that is not the closest DC for the retailer among the other open DCs. Assigning these 11 retailers to DCs by only considering local delivery costs would increase the total costs about 3.5%. Table 5.8 shows the retailers, which are assigned to non-closest DCs for the base case.

Table 5.8: Retailers Assigned to Non-closest DCs

Retailer	Closest DC	DC Assigned
63	12	1
10	54	3
42	3	71
51, 70	1	71
24, 28, 29, 53, 61, 69	12	71

5.2.2. The Constructive Type Algorithm

The results obtained for the multi item location/inventory problem by implementing the constructive type algorithm for the base case is presented in Table 5.9. The objective function values achieved by the constructive type algorithm for each value of p is given in the third column of the table. In fact, the constructive type algorithm could be terminated at the point where the objective function starts to increase. However, we do not stop the algorithm at that minimum point on purpose in order to check the changes in the objective function value after attaining the minimum point, as we also did for the improvement type algorithm. Observing the results of the constructive type algorithm for the base case, no such instance is observed, in which the objective function value decreases again after the minimum point. The computation time of the algorithm presented in the table corresponds to the point where the objective function value starts to increase.

The total cost of the solution, which is obtained by solving the p-median problem to initiate the improvement type algorithm, is also presented in the second column of the Table 5.9 in order to realize the improvement obtained by the constructive type algorithm and compare the solution qualities of the two heuristic algorithms. When we examine the results obtained by the constructive type algorithm, it is observed that the solutions from the two heuristics are similar but not identical for the base case. The constructive type algorithm also suggests opening 5 DCs at the same locations as the improvement type algorithm does. Moreover, there is no difference between the two heuristics in the retailer assignments, and in the total cost values of the best solution obtained. However, it is observed that there are differences between the heuristics in terms of the solutions obtained for different values of p.

When we compare the performance of the two heuristics in the base case, we see that the constructive type algorithm always gives better solutions than the improvement type algorithm when it is initialized with p-median clusters. Also, it gives either the same or better values than the randomly initialized improvement type algorithm until p is increased to 11. The better objective function values

Table 5.9: The Results of the Constructive Type Algorithm for the Base Case

	Objective function			DCs opened						Cost composition			
p	p-med. (initial)	constructive	% improvement							shipping	fixed	safety	order+inv
1	3,049,318.525	3,049,318.525		6						2,866,541.910	135,456.000	10,777.059	36,543.556
2	2,963,248.887	2,878,728.838	2.85%	6	80					2,629,923.750	184,330.000	13,698.700	50,776.388
3	2,838,092.511	2,743,029.411	3.35%	6	54	80				2,439,041.760	222,741.000	17,680.081	63,566.570
4	2,714,194.855	2,639,629.141	2.75%	1	6	12	54			2,256,484.860	291,154.000	19,925.922	72,064.359
5*	2,675,368.875	**2,553,300.023**	4.56%	**1**	**3**	**12**	**54**	**71**		2,173,224.960	277,024.000	22,290.606	80,760.456
6	2,678,427.079	2,553,440.737	4.67%	1	2	3	25	54	71	2,130,097.860	312,495.000	23,891.685	86,956.191
7	2,676,800.023	2,564,364.366	4.20%							2,072,114.400	373,572.000	25,417.580	93,260.386
8	2,647,764.362	2,578,821.414	2.60%							2,044,822.800	409,737.000	26,233.150	98,028.464
9	2,716,500.417	2,603,025.854	4.18%							2,023,858.290	447,248.000	27,671.273	104,248.291
10	2,717,875.663	2,618,835.448	3.64%							2,030,875.635	451,378.000	28,146.382	108,435.430
11	2,755,924.438	2,644,072.297	4.06%							2,019,531.495	482,473.000	29,446.673	112,621.128
12	2,795,366.582	2,668,979.903	4.52%							2,030,605.455	488,200.000	30,699.449	119,474.999
13	2,841,316.718	2,695,725.251	5.12%							1,987,101.945	548,901.000	32,536.746	127,185.560
14	2,863,434.727	2,729,817.711	4.67%							1,982,595.255	581,777.000	33,494.305	131,951.151
15	2,917,834.425	2,759,965.211	5.41%							1,932,334.845	656,826.000	34,208.875	136,595.491

Computation time in seconds (up to the increase in obj. fnc): 55

Overall Improvement with respect to p-median solution: 3.57%

obtained by the improvement type algorithm at the values of p being equal to 11,13, and 15 do not affect our solution. Although it is risky to generalize from a single problem instance, it can be said the constructive type heuristic dominates the improvement type heuristic in solution quality when the latter is initialized with p-median clusters. Also, the constructive type heuristic is superior in solution time than the randomly initialized improvement type algorithm and not worse off in terms of the solution quality.

Since the constructive type algorithm has achieved the same solution with 5 DCs, the analysis performed for the improvement type algorithm on the best solution is also agreeable for the constructive type algorithm. However, since the solutions obtained for other values of p are generally different for the two heuristics, an evaluation for the constructive type heuristic corresponding to these different values of p is needed. As described before, the constructive type algorithm proceeds by incrementing the number of DCs to be located by one at each iteration. When we look at the results for the DCs opened at each iteration, it is observed that the set of DCs located by the algorithm at various level of p is not an exact subset of the set of DCs corresponding to the best objective function value achieved through the algorithm. This means that our constructive type heuristic does not proceed by fixing the DCs located at each iteration; the location of the DCs can change at any point during the reallocate and interchange procedures applied by the heuristic.

Figure 5.4 represents the behaviour of the total cost and its components according to the results obtained by the constructive type algorithm. Although the solutions of the constructive and improvement type heuristics are not exactly the same for some values of p, it is observed that the cost components follow the same trend as the value of p is altered. The shipping costs decrease as the number of distribution centers located increases while the fixed costs, safety stock costs, and joint order and average inventory costs increase as more DCs are located. As explained before, the total cost attains its minimum at the point where the balance between the decreasing shipping costs and increasing fixed and inventory costs is achieved.

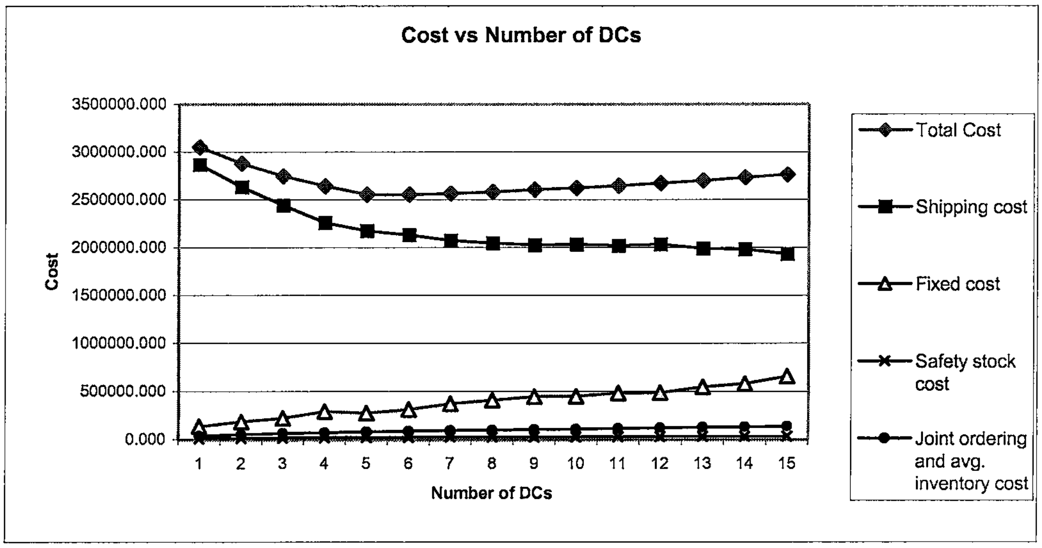

Figure 5.4: Representation of the Costs as a Function of the Number of DCs for the Constructive Type Heuristic

5.3. Sensitivity Analysis

Sensitivity analysis is based on the idea of setting up a family of runs by altering a single adjustable parameter for the selected component of the model. Geoffrion (1979) gives some examples about the situations where the application of sensitivity analysis is appropriate and beneficial. The reasons to apply sensitivity analysis, which are also valid for our distribution design problem, can be stated as follows:

- When there is uncertainty for the estimates of the model data, sensitivity analysis on these data may show that there is no significant dependence of the model solution over the range of uncertainty.
- When there is possibility that certain data will change over time, sensitivity analysis helps to determine how the solution would change in response.
- Sensitivity analysis helps to develop insights into the workings of a system; that is, it is a tool with which "whys" behind the "whats" can be found out.

We choose to apply sensitivity analysis to the following parameters of our model by considering the reasons above:

- Inventory holding cost and transportation cost parameters
- The ordering cost parameters
- The demand variance of the items

5.3.1. Sensitivity Analysis Based on the Inventory and Transportation Costs

In this section, sensitivity analysis is performed by altering the inventory and transportation cost parameters. The reason for performing sensitivity analysis for these cost terms is to understand the relation between them better, test the effects of the changes on the results and to compensate for the inaccuracies in the estimation of the related parameters.

The relative importance of the inventory and transportation costs in the total cost is modified by giving weights to the corresponding cost terms as follows:

α: Weight given to transportation costs

β: Weight given to the inventory holding costs

Four levels of α are used for the sensitivity analysis in our computations. Also, a set of β is determined corresponding to each value of α. In this way, a total of 30 scenarios are created to question the robustness of the solutions for different problem instances. The values of α and β that are used for the sensitivity analysis are provided in Table 5.10.

Table 5.10: Weights Given to Transportation and Inventory Costs

		β							
α	0.5	0.5	1	2	5	7.5	12.5	25	
	1	0.5	1	2	5	15	25	50	
	2	0.5	1	2	5	10	30	50	100
	5	0.5	1	2	5	25	75	125	250

The base case problem corresponds to the situation when both transportation and inventory parameters have a weight of 1, i.e. α and β are equal to 1. We have analyzed the solutions obtained for the base case in the previous sections. In this section, the problems created by different values of α and β, and the results obtained for these instances are analyzed. All of these problem instances that are generated for the sensitivity analysis are solved using both improvement type and constructive type algorithms. When applying the improvement type algorithm, the initial clusters are generated by the two methods: the solution of the p-median problem and random clusters. Also, as we did for the base case, we do not terminate the improvement type and constructive algorithms at the point where the objective function value starts to increase and we perform additional iterations for all the instances to check whether there exists another local optima point or not. It is observed that there can be such cases in which the objective function attains its minimum after the first local optima point. All the results including the objective function values, the number and location of the DCs, the composition of the total cost, and the solution times obtained by each heuristic are presented in APPENDIX C.

According to the results it is observed that, the heuristics do not attain exactly the same solution for some problem instances. Therefore, we make our analysis on the solution of the heuristic, which gives the best result for each specific instance. In our analysis, we question how the objective function value, the number and location of DCs, the cost components, and the solution times of the algorithms respond to the changes in the inventory and transportation cost weights.

First, when we analyze the changes in the objective function values as the inventory and transportation cost parameters are modified, we observe the same trend in the results obtained by each heuristic. Then, we combine the results of the heuristics by choosing the best objective function value obtained by any one of the heuristics for each value of α and β. Figure 5.5 shows the trend followed by these best values for each scenario. According to the figure, the objective function increases when weights given to the transportation and inventory costs are increased. When α is increased to a higher level, the total cost curve shifts upwards. Also, when we increase the value of β for a particular level of α, we obtain a higher objective function value on the same total cost curve.

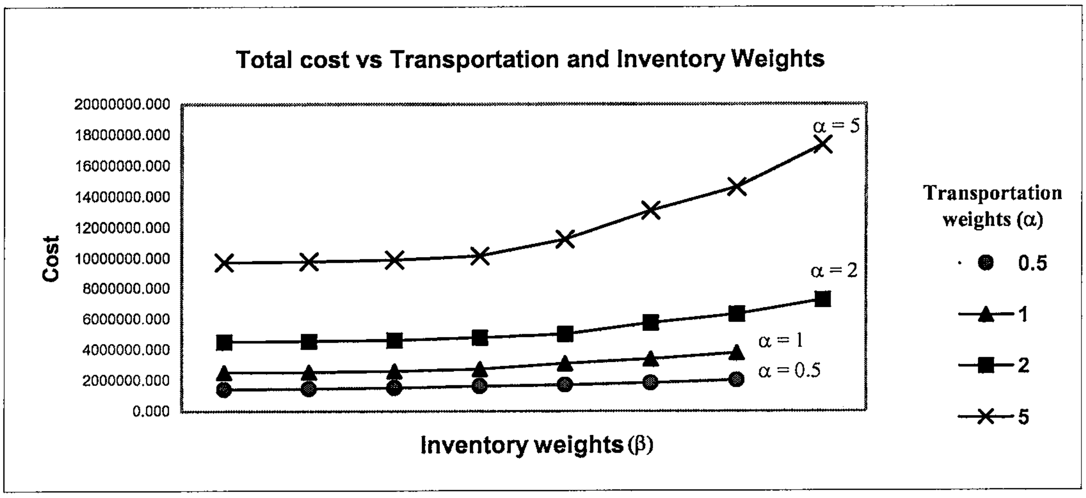

Figure 5.5: The Sensitivity of the Objective Function Value to Inventory and Transportation Cost Parameters

Next, the sensitivity of the number and location of the DCs to the transportation and inventory cost parameters is questioned. Table 5.11 shows the number of DCs located corresponding to minimum objective function values obtained by applying the improvement and constructive type heuristics for each value of α and β. In the table, the heuristics, which give the minimum cost solution for a particular level of α and β, are indicated by (**). Also, the heuristics, which suggest opening the same number of DCs at a higher cost, are marked by (*). When we compare the performance of the heuristics, we cannot conclude that one of them always gives better objective function values than the others. However, it is observed that for the set of problems in which α values are equal to 0.5, 1 or 2, the best solutions are obtained most of the time by the constructive type heuristic or the improvement type heuristic that is started with randomized clusters. On the other hand, when the weight given to transportation weight,α, is increased to 5, the best objective function values are obtained by the improvement type heuristic, which is initialized by the clusters obtained by the p-median solution, for each value of β. Then we can say that when the unit transportation costs are relatively higher and their dominance on the inventory costs is increased, the chance of attaining the best solution by the improvement heuristic initialized by the p-median clusters becomes also higher for our problem. This result is intuitive since as the transportation costs become dominant, the effect of inventory costs on the final solution may decrease, and the solutions are then closer to the p-median problem's solutions.

Table 5.11: The Number of DCs Located for Different Values of α and β

				Improvement	
α	β	Number of DCs	Constructive	p-med.	rand
0.5	0.5	5	**	*	*
0.5	1	5	**	*	*
0.5	2	5	*	*	**
0.5	5	3	**	*	**
0.5	7.5	3	*	*	**
0.5	12.5	2	**	*	**
0.5	25	1	**	**	**
1	0.5	6	**		
1	1	5	**	**	**
1	2	5	*		**
1	5	5	*	*	**
1	15	5	**	*	**
1	25	3	*		**
1	50	1	**	**	**
2	0.5	11	**		
2	1	11	**		
2	2	11			**
2	5	8	*	**	
2	10	8	*	**	
2	30	5	*	*	**
2	50	4	**		**
2	100	2	**		**
5	0.5	20		**	
5	1	20		**	
5	2	20	*	**	
5	5	19	*	**	
5	25	16		**	
5	75	8		**	
5	125	6	*	**	*
5	250	2	*	**	*

Also, as observed in Table 5.11 we can conclude that the number of the DCs is sensitive to both transportation and inventory weights. Figure 5.6 shows the sensitivity of the number of the DCs to changes in both transportation and inventory cost weights. It is seen that when the weight of the transportation costs is increased, the number of DCs located also increases. Also, when the weight of inventory costs is increased while fixing the transportation cost weight, the number of DCs decreases. This is because when α is large, the transportation term becomes more significant in the objective function, making it desirable to have more DCs. Similarly as β increases, the number of DCs decrease because inventory becomes more expensive and risk-pooling becomes more attractive. We also observe that when we increase both α and β, the number of DCs located increases on the average.

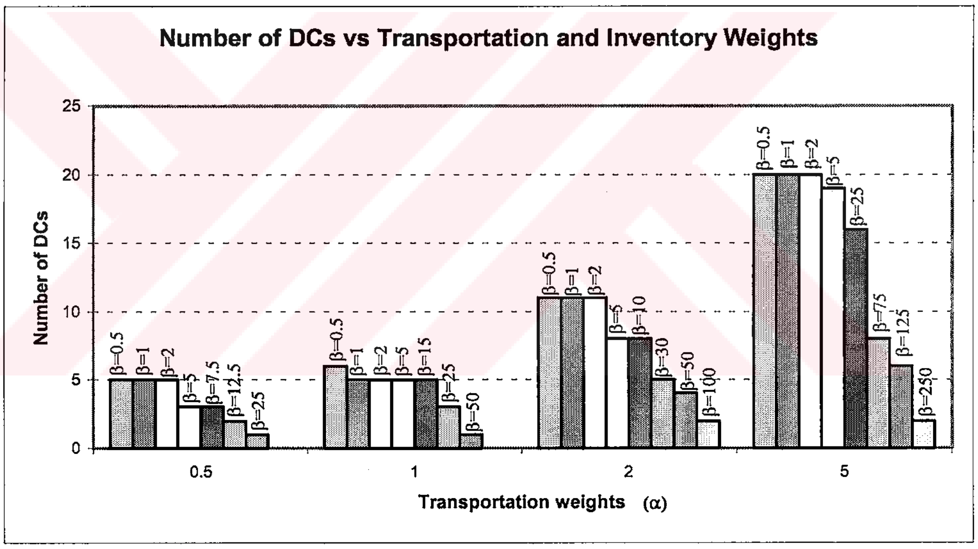

Figure 5.6: Sensitivity of the Number of the DCs to Inventory and Transportation Cost Parameters

Also, the retailer locations that are chosen as DCs in different scenarios can be seen in Table 5.12. The first column of the table represents the codes of the retailers, where a DC is located in one of the scenarios. According to these results, it is seen that for a given value of α the location of DCs may or may not change as the value

Table 5.12: Results for the Location of the DCs for the Problems with Different Values of α and β

	α = 0.5							α = 1							α = 2								α = 5							
	β = 0.5	β = 1	β = 2	β = 5	β = 7.5	β = 12.5	β = 25	β = 0.5	β = 1	β = 2	β = 5	β = 15	β = 25	β = 50	β = 0.5	β = 1	β = 2	β = 5	β = 10	β = 30	β = 50	β = 100	β = 0.5	β = 1	β = 2	β = 5	β = 25	β = 75	β = 125	β = 250
1								√	√	√	√	√	√		√	√	√	√	√	√	√		√	√	√	√	√	√	√	
2								√							√	√	√													
3	√	√	√					√	√	√	√	√								√							√	√		
6							√						√	√	√	√	√	√	√		√	√	√	√	√	√	√	√	√	√
10																							√	√	√	√				
12	√	√							√	√	√	√								√	√									
16																											√			
19																											√			
20																							√	√	√	√				
21																		√	√				√	√	√	√	√	√	√	
25			√					√					√		√	√	√	√	√				√	√	√	√	√	√		
26																							√	√	√	√				
28																							√	√	√	√	√			
31																							√	√	√	√				
32															√	√	√	√	√				√	√	√	√	√			
33	√	√																					√	√	√					
34															√	√	√						√	√	√	√	√			
38															√	√	√										√			
40																							√	√	√	√				
41																												√	√	
42																							√	√	√	√	√			
45															√	√	√	√	√				√	√	√	√	√	√		
46																						√	√	√	√	√	√			√
49															√	√	√						√	√	√	√	√			
52																													√	
54	√	√	√	√	√	√		√	√	√	√	√			√	√	√	√	√	√	√		√	√	√	√	√			
55															√	√	√	√	√				√	√	√	√		√		
60																							√	√	√	√				
64																													√	
71	√	√	√	√	√	√		√	√	√	√	√								√										
80				√	√																									

of β is altered. For example, when α is equal to 1, we obtain the same DC locations when the β values change between 1 and 15. Also, when all the results given by the other α and β values are observed, it is seen that if the increases in the β values are not very significant to affect the solution in terms of the number of DCs opened, the DCs are opened at the same locations for this range of β values. However, if the importance of the inventory costs are increased significantly and there exists a decrease in the number of DCs opened, we observe that the set of the DCs opened is not necessarily a subset of the set of the DCs opened for lower values of β. That is, the set of DCs may change with the multiple deletion and addition of the new DCs. Also, we see that the set of DCs is more sensitive to the changes that occur in the transportation costs in our problem instances. Another observation is that when theinventory weights are increased such that the solution favors opening only a single DC, and that DC is located in Ankara (node 6), where the single supplier is located. This can be interpreted as the tendency of the system to become completely centralized when the inventory costs are very high.

In order to check the effects of the different inventory and transportation cost parameters on the composition of the total cost, we consider some cases and make comparisons among them. We analyze the base case (α=1, β=1), whose solution suggests opening 5 DCs, as discussed in the previous section. For the base case, shipping costs, fixed costs, joint ordering and average inventory costs, and safety stock costs constitute 85%, 11%, 3%, and 1% of the total cost, respectively. When the weight given to inventory cost parameter (β) is increased to 25, the number of DCs located decreases to 3 and the composition of the costs occur as represented in Figure 5.7. When the inventory cost parameter is increased, it is seen that the

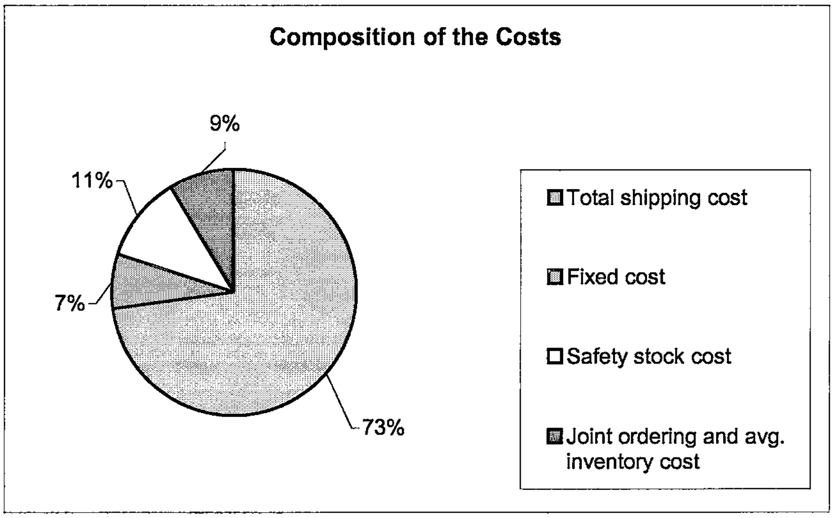

Figure 5.7: Distribution of the Costs for α =1, β =25

percentages of the total shipping costs and the fixed costs in total cost are decreased. Moreover, it is observed that the safety stock cost and joint ordering and average inventory costs constitute a higher percentage of the total cost value.

As mentioned before, when inventory considerations dominate (β is very large relative to α), it is sometimes more economical to assign some retailers to a DC that is other than the least cost DC in terms of local delivery costs. That is, when the inventory costs are taken into account, assignment to the closest facility is not always optimal due to the risk pooling effects. According to the solutions of the base case, 11 retailers are assigned to DCs other than the one resulting in the smallest local delivery costs. In order to check whether there exists a relation between the number of such non-closest assignments and the level of the inventory cost parameters, we consider some instances with varying levels of inventory and transportation cost levels. When the weight given to inventory costs (β) is increased to 25, the number of retailers, which are assigned to non-closest DCs, is 13. Although the increase in the number of non-closest assignments as the inventory costs become more dominating seems intuitive, we can find counterexamples in which the number of non-closest assignments is decreased when the inventory costs are significant. For example, we obtain 23 non-closest assignments according to the solution of the problem with $\alpha=2$ and $\beta=2$. When the inventory costs are increased significantly for this problem by setting $\beta=100$, the number of non-closest assignments decreases to 13.

Also, we search whether computation time of the algorithms is sensitive to the changing inventory and transportation cost parameters. As presented in Figure 5.8, as the importance of the transportation costs is increased, the computation time of the constructive heuristic gets longer on the average. Also, we observe a general fall in the computation time when the weight of inventory costs is increased. On the other hand, the computation times for the improvement heuristic seem not to follow an order according to the increasing inventory weights. However, when we compute the average computation time that passed for the all the runs for a given value of α, we observe the following trends, which are shown in Figure 5.9 and Figure 5.10.

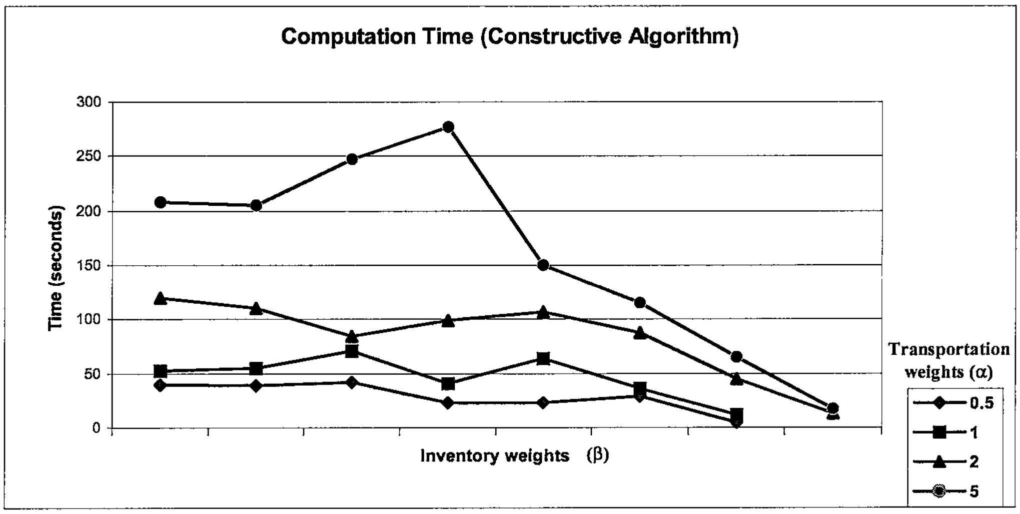

Figure 5.8: Sensitivity of the Computation Time to the Inventory and Transportation Weights for the Constructive Type Algorithm

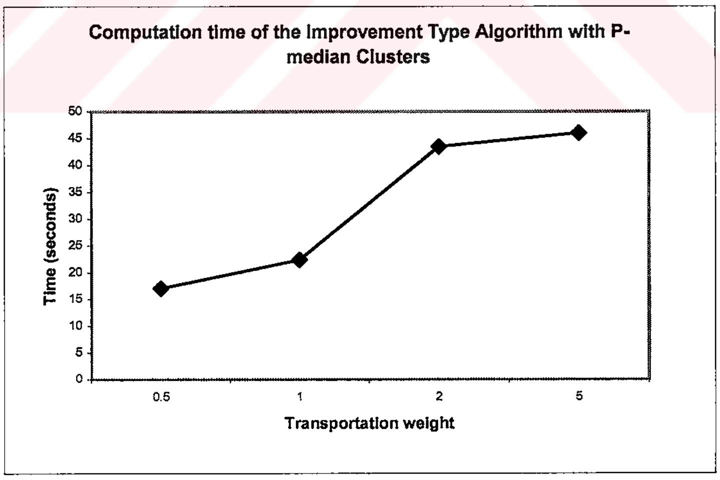

Figure 5.9: Average Computation Time of the Improvement Type Heuristic Initiated with P-median Clusters versus Transportation Weights

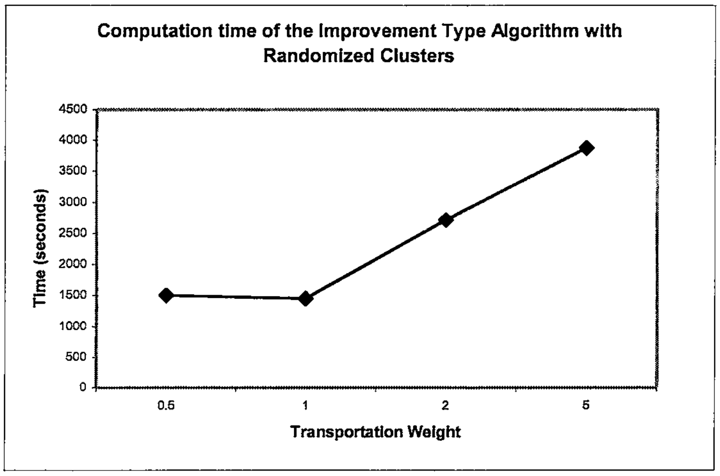

Figure 5.10: Average Computation Time of the Improvement Type Heuristic Initiated with Randomized Clusters versus Transportation Weights

5.3.2. Sensitivity Analysis Based on the Ordering Cost Parameters

The results of the sensitivity analysis performed on the ordering cost parameters are presented in this section. We consider how the solution might change if the cost of ordering is decreased significantly as might be the case with e-commerce technologies. In our case, the ordering cost has two components due to the multi-item characteristics of our problem and the inclusion of the joint replenishment costs. One of them is the major ordering cost, which is charged at each replenishment independent of the order size and the items included in each order. On the other hand, minor ordering cost associated with each item is charged when the item is included in a specific order.

In the previous analysis performed for the base case, the values of the major ordering cost, A_j, at each DC are obtained by computing U[450, 550] +0.1*(distance$_j$) , and rounding the result to the nearest integer. Minor ordering costs are generated by rounding the number given by U[A_j/20, A_j/10] to the nearest integer. For the sensitivity analysis to be performed in this section, major ordering cost parameter is decreased significantly and evaluated at U[10, 20]

+0.1*(distance)$_j$. The minor ordering costs are assumed to be still dependent on major ordering costs, and generated using the same parameters of the uniform distribution. Then the effects of this significant decrease in both parameters on the results are questioned for a number of different cases. Initially, we performed the sensitivity analysis for the base case, that is, by keeping all the parameters fixed and altering only the ordering cost parameters. Then, the same analysis with reduced ordering costs is also repeated for the problem settings in which the weight given to the inventory cost parameter (β) is also changed. This analysis is applied for three levels of β, while keeping the weight given to the transportation costs (α) fixed at its base level in each instance. APPENDIX D contains all of the results for the problems with the reduced order costs obtained by applying the improvement and constructive type algorithms. In Table 5.13, the results that correspond to the best solution obtained by the heuristics are summarized.

Table 5.13: The Effect of the Reduced Ordering Costs on the Total Cost and the Number of DCs Opened

		Aj ~U[450, 550] +0.1*(distance)j		Aj ~U[10, 20] +0.1*(distance)j	
α	β	Number of DCs located	Objective fnc.	Number of DCs located	Objective fnc.
1	1	5	2553300.023	6	2493406.468
1	15	5	3097000.939	5	2879187.973
1	25	3	3394182.290	5	3127914.924

As we observe from Table 5.13, the objective functions attained through reduced ordering costs is lower than the previous results obtained for each of the problems with different inventory cost weights. Also, the number of DCs is increased on the average when the ordering costs are decreased. The reduced ordering cost affects the solution most when the weight of the inventory costs (β) is increased to 25. The locations of the DCs for each of these instances are presented in Table 5.14. According to table, at the instance in which the number of the DCs is not sensitive to the reduced ordering costs (α=1, β=15), the locations of the DCs are also identical. However, when there is an increase in the number of DCs due to reduced ordering costs, we see that some DCs are deleted from the solution set and new locations are added to the opened DC set.

Table 5.14: The Effect of the Reduced Ordering Costs on the Location of the DCs

α	β	Aj ~U[450, 550] +0.1*(distance)j	Aj ~U[10, 20] +0.1*(distance)j
1	1	1, 3, 12, 54, 71	1, 2, 3, 25, 54, 71
1	15	1, 3, 12, 54, 71	1, 3, 12, 54, 71
1	25	1, 6, 25	1, 3, 12, 54, 71

In Figure 5.11, the cost composition of the best total cost achieved for the problem with the reduced order costs is represented. When this cost breakdown is examined and compared to that of the base case with high level of ordering costs, it is seen that the percentage of the fixed costs in total costs is increased due to locating additional DCs. Moreover, the portion of the joint ordering and average costs in the total costs decreased from 3% to 1%. The portions of the shipping costs and the safety stock costs in total costs are not affected by the changes made in the ordering costs.

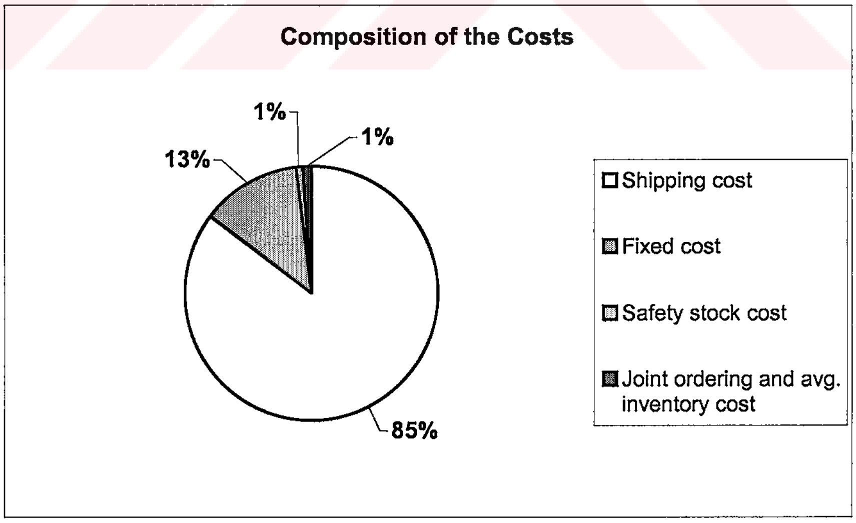

Figure 5.11: Distribution of the Costs for the Reduced Order Cost case (α =1, β =1)

When we examine the solutions of the problems with α =1 and β =25 in terms of their cost compositions for different order cost levels, similar results are obtained. The shipping costs, fixed costs, safety stock costs, and joint ordering and average inventory costs constitute 73%, 7%, 11%, and 9% of the total cost when the ordering costs are at the high levels. When the ordering costs are reduced, the distribution of the costs occurs as presented in Figure 5.12. According to figure, the percentage values of all cost components are changed with respect to the portions they constitute in the problem with high order cost levels. It is observed that the share of the total fixed costs in the total cost is increased while the percentage of joint ordering and average inventory costs is decreased. Also, we observe some changes in the compositions concerning the total shipping costs and the safety stock costs. Since the number of DCs located is increased from 3 to 5 when the order cost level is reduced, the shipping costs constitute a lower percentage of the total costs, while the safety stock costs have a higher percentage.

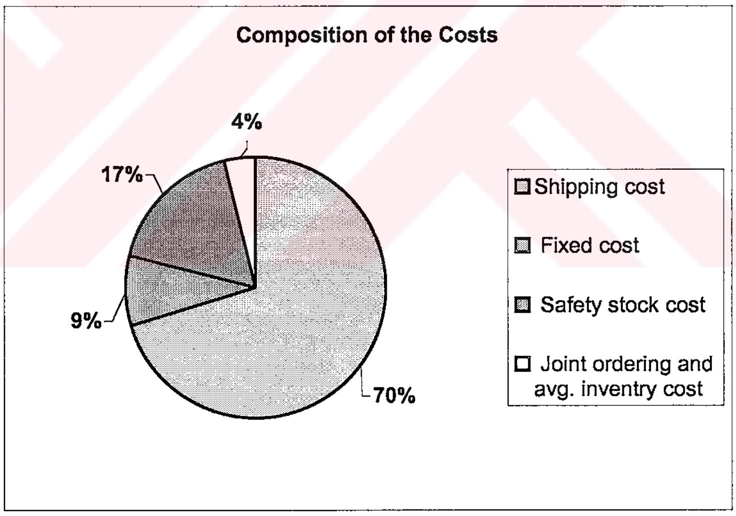

Figure 5.12: Distribution of the Costs for the Reduced Order Cost Case (α =1, β =25)

The total decrease observed in the joint ordering and average inventory costs can be explained by considering the importance of the ordering cost levels on the inventory policies. When the ordering cost is decreased, the frequency of replenishments and the amount ordered for each type of item may change at the DCs. DCs give more frequent orders with smaller order amounts when the ordering cost is lower, and this results in smaller amount of average inventory kept at the DCs. Also note that, the change in the cost compositions related to safety stock costs can not be considered as the effect of the changing ordering cost values directly, since this type of inventory is not related to the level of the ordering costs. The changes in the cost compositions associated with the safety stock and the total shipping costs are mainly due to the increased number of DCs located as a result of the reduced ordering cost levels.

Since the average distance between the retailers and the DCs is reduced when the number of DCs located is increased due to reduced ordering costs, we can say that the results obtained by lowering the ordering costs agrees with one of the main objectives of the e-commerce, which is improved customer service.

5.3.3. Sensitivity Analysis Based on the Variance of the Demand

In our problem, the annual demand associated with each retailer is assumed to follow a Normal distribution. The parameters of the Normal distribution are generated based on the population data of the demand locations for the base case. The mean annual demand for each item is determined by dividing the population by a constant and the demand variance is obtained by setting a CV (coefficient of variation) level for each type of item.

The mean and the variance of the demand for each type of item may change over time. In this section, we perform sensitivity analysis on the demand variance to see how the solutions respond to another setting with different levels of CV set for each type of item. The CV levels defined for the sensitivity analysis -referred as low CV- are presented in Table 5.15. Also, the CV levels, which are used in our base case, can be seen in the same table.

Table 5.15: Coefficient of Variation Levels of Demand for the Items

	Item 1	Item 2	Item 3	Item 4
Low CV	0.03	0.05	0.05	0.06
High CV (base case)	0.2	0.4	0.4	0.5

After resetting the base case problem by using low CV values, both improvement and constructive type heuristics are used to solve the problem. Both algorithms are applied to different settings with low CV, in which the inventory costs are also changed by giving different weights to the inventory cost. While keeping the weight of the transportation costs at the base level, three additional problems are generated in this way to test the effects of low CVs. All the results are presented in APPENDIX E.

Observing the results of both algorithms, we can not conclude that one of the algorithms performs better than the other in terms of solution quality for the low CV case. The results presented in Table 5.16 correspond to the best solutions obtained either by the constructive or improvement type algorithm. As observed in Table 5.16, when the CV is changed from high level to low level, some changes are observed in the number of DCs opened and the objective function values. First of all, it is seen that the number of DCs opened for the high CV case is less than or equal to the number of DCs opened in the low CV case, for the same level of α and β. Also, the objective function values of the problems with high CV levels are greater than those of the problems with low CV levels. The tendency of locating less DCs as the demand variation is increased can be explained by the risk pooling concept. As CV is increased, there is higher incentive for the system to be centralized to achieve risk pooling benefits. That is, when the demand variability is higher, the demand is aggregated in smaller number of DCs, since it becomes more likely that high demand from one retailer is offset by low demand from another. Also, as observed in Table 5.17, when the variation level is changed from low to high, the smaller set of DCs located in the high variance setting is not a subset of the set of DCs opened in the low variance setting for the base case with α and β being equal to 1. Also, for the cases with α=1, β =25 and α=1, β =50, the set of DCs opened in the high CV setting is not a subset of the DC set suggested by the low CV setting. When α=1 and β =15, the number and location of the DCs do not change.

Table 5.16: The Effects of CV on the Solutions

		Low CV		High CV	
α	β	Number of DCs located	Objective fnc.	Number of DCs located	Objective fnc.
1	1	6	2532477.008	5	2553300.023
1	15	5	2805214.636	5	3097000.939
1	25	5	2924354.199	3	3394182.290
1	50	5	3161785.270	1	3799252.820

Table 5.17: The Effect of CV on the Location of the DCs

α	β	Low CV	High CV
1	1	1, 2, 3, 25, 54, 71	1, 3, 12, 54, 71
1	15	1, 3, 12, 54, 71	1, 3, 12, 54, 71
1	25	1, 3, 12, 54, 71	1, 6, 12
1	50	1, 3, 12, 54, 71	6

As explained before, the safety stock level in a centralized system is proportional to the square root of the variance of the demand. Hence, when the demand variance is high, more safety stock inventory is maintained at the DCs to achieve the desired service level against high demand variances. As a result, when the variance of the demand is changed from high to low setting, a decrease in the total amount of safety stock is observed. Figure 5.13 represents the composition of the costs for the problem in which the variation levels for each type of item are determined by low CV values, for α=1 and β= 25. It is observed that the percentage of the safety stock cost is decreased by 9 points with respect to the results of the problem with high CV values. On the other hand, the contributions of the total shipping costs, fixed costs and joint ordering and inventory costs to the total cost are increased in terms of percentage values for the problem with low variance setting. The values of fixed costs and joint ordering and average inventory costs are higher, when the CV is set to low level, due to the increase in the number of DCs in the solution set. Moreover, although the total shipping costs constitute a higher percentage of the total cost in the low CV setting, in fact, the total dollar value of the shipping costs is decreased with respect to the problem with high CVs.

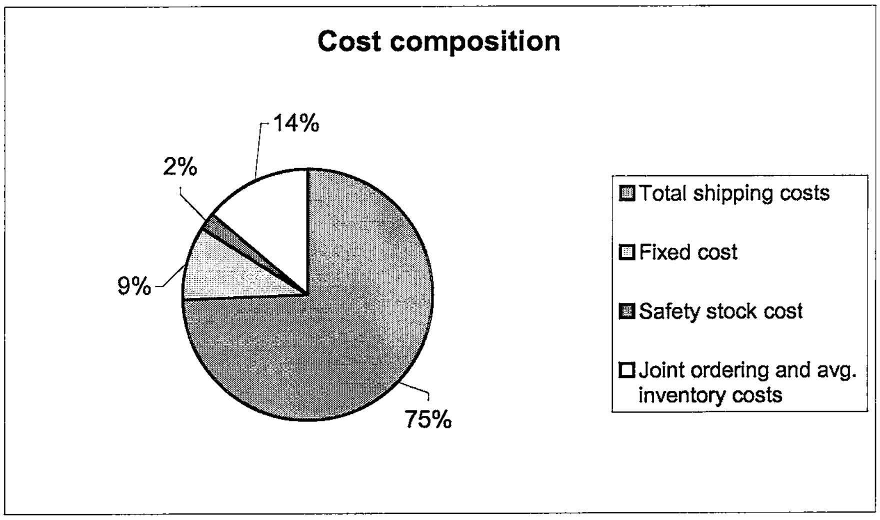

Figure 5.13: Distribution of the Costs for the Low variance Problem Setting (α =1, β =25)

The change in the safety stock costs under the changing demand variation levels and inventory cost weights is also represented in Figure 5.14.

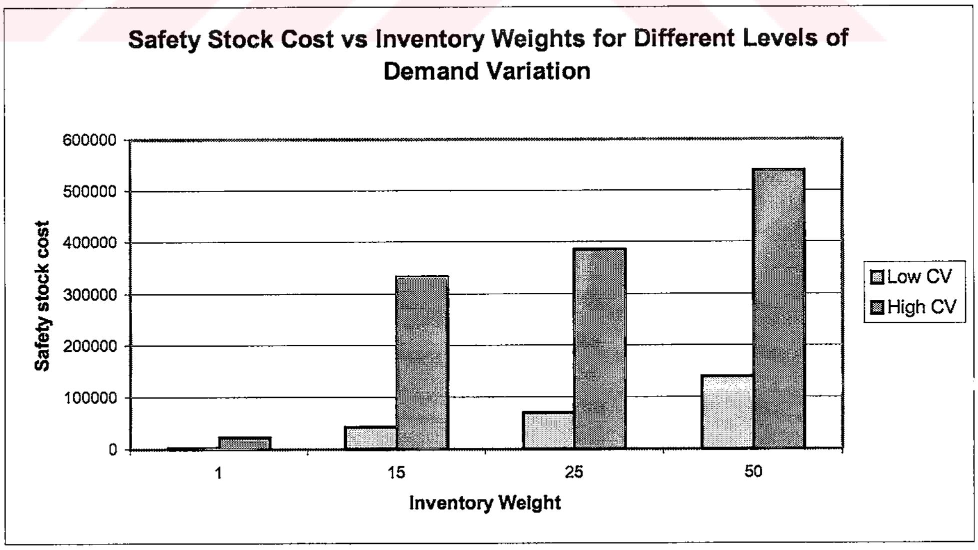

Figure 5.14: Safety Stock Costs versus Inventory Weights for Low and High Levels of Demand Variation

CHAPTER 6

CONCLUSIONS

The literature on supply chain management classifies problems in three levels: strategic (long term), tactical (medium term), and operational (short term). The usual approach to solve these problems has typically been to tackle them in isolation from one another. This approach fails to take the interaction of the decisions at different levels into account, and tends to promote incompatibilities and incoherence between each level of the supply chain.

In this study, we consider the decisions related to the distribution stage of a supply chain. We focus on the location/allocation decisions at the strategic level and inventory related decisions at the tactical/operational level. The traditional location/allocation models seek optimal solutions by considering only the transportation and fixed facility costs and ignoring the inventory costs. On the other hand, the inventory models assume that the location/allocation decisions are already made; that is, these problems are handled independently until recent studies, although they decisions are closely related. The findings of the recent studies that deal with the integrated location/inventory problems reveal the significance of the integration of these decisions for effective supply chain management.

Our aim is to incorporate tactical/operational inventory decisions into the strategic level location/allocation decisions while designing a distribution system. The main difference of our study from the other studies that address integrated inventory/location problems is that we consider a distribution system in which multiple items are delivered from the single supplier to the retailers through the DCs, and the control of multiple items' inventories necessitates the application of a multi-item inventory policy at the stocking locations.

The distribution system we address consists of a single supplier, a number of retailers, and distribution centers (DCs), which are located at some of the retailer locations. The retailers face with stochastic demand for a number of items. Due to the uncertain demand, some amount of safety stock is maintained to satisfy the customer demand with acceptable service levels. The safety stock is maintained only at the DCs to achieve the benefits of risk pooling. We ignore the small amount of inventory maintained at the retailers. The DCs order the items from the single supplier under the joint replenishment policy and satisfy the customer demand that occur at the retailers only. By the implementation of a joint replenishment policy at the DCs, we aim to achieve the savings that result in the ordering costs by grouping some of the items in a single order. Our problem is determining the number and location of DCs and the assignment of the retailers to the open DCs by considering the cost implications of the inventory policies followed at each DC as well. We assume that a modification of the (R,S,s) type periodic review inventory control system is implemented at the DCs. However, due to the difficulty and complexity of the exact analysis of the (R,S,s) system especially in a multi-item joint replenishment environment, we have used some approximations and simplifications in representing the inventory policies in our distribution design problem. First of all, we handle the multi-item inventory control problem assuming that the demand is deterministic. Then the results provided by the deterministic joint replenishment policy are assumed to be implemented at the DCs. Also, we are not dealing with the exact operational inventory control policy parameters in this strategic problem, since these parameters are subject to change in the long term. Therefore, we approximate the cost effects of the multi-item inventory control system in the total cost by using a lower bound derived for the cost of the 'best' joint replenishment policy in Silver, Pyke and Peterson (1998).

We have formulated a non-linear integer programming model that minimizes the fixed facility costs, transportation costs between the supplier and the distribution centers, and between the distribution centers and the retailers, safety stock inventory costs, and joint ordering and average inventory costs at the distribution centers. The nonlinear terms due to the safety stock costs and joint ordering and average inventory costs increase the difficulty in solving this model. Moreover, the addition of the implications of the joint replenishment policy in the model brings the requirement of distinguishing the items as the base items and nonbase items for each DC to be located. In order to find which item is the base item for a DC, we should evaluate the setup cost/sales volume ($) ratio for each type of item at each distribution center using the JRP heuristic. Since we do not know the assignment decisions, and hence the amount of demand assigned to each DC for each type of item, we need a solution approach that not only accommodates the use of the JRP heuristic, but also allows solving the model in an integrated way.

Two heuristic type algorithms are developed to solve the integrated location/inventory model: improvement type algorithm and constructive type algorithm. Briefly, the improvement type algorithm starts with a feasible solution, with a number of DCs located and retailers assigned to these DCs. Then a better solution is searched in the neighborhood by using some local search procedures. The algorithm is run for each value of number of DCs (p) until the minimum objective function value is achieved. The initial feasible solutions to start the improvement type algorithm is obtained either randomly or by using the solution of the p-median problem. In the constructive type heuristic, the first facility is located in such a way that the total cost is minimized. Then the facilities are added one by one, each time selecting the location that most reduces the total cost, and applying a number of improvement methods in the constructive type algorithm.

We test both heuristic algorithms on the problem instances generated, which consists of 81 nodes. The computational results obtained by each heuristic are compared to the solution of the p-median problem, which is solved to initiate the improvement type algorithm. It is observed that we can obtain cost reduction when we solve the problem in an integrated way rather than solving it by p-median problem that considers only the local delivery costs. In addition, the number of distribution centers located can be lowered when our integrated model is used instead of the p-median model. We have also performed some sensitivity analyses with respect to the inventory, transportation, and ordering costs and the variability of the demand. The sensitivity analysis reveal the relations between the cost components better and provide a range of alternative solutions against the changes in the parameters of these cost components. It is found that when the importance of inventory costs is increased or the importance of the transportation costs is decreased, the number of facilities located decreases. Furthermore, when fixed ordering costs from the DCs to the supplier are reduced significantly, more distribution centers are located. It is also observed that number of distribution centers opened under high demand variation level is less than or equal to the number of distribution centers opened in the low variation case.

Moreover, the solutions given by each heuristic are compared among each other in terms of the solution quality and solution times for each problem instance. According to the results, it is found that it is difficult to favor one of the heuristics according to the quality of the solutions obtained. However, it is seen that the best objective function values are mostly obtained by the constructive type algorithm and/or the improvement type algorithm that is started using random clusters. The improvement type algorithm that is initiated by the clusters obtained using the p-median problem perform better than the other algorithms, when the importance of the transportation costs is increased significantly. The solution times of all the algorithms can be regarded as low and even negligible, when the strategic nature of the problem handled is considered. The computation time recorded for the constructive type algorithm and the improvement type algorithm initiated with p-median clusters are mostly less than a minute. On the other hand, the solution time of the randomly initiated improvement algorithm is much longer since the algorithm is applied to many different initial solutions; but it can still be considered as reasonable when the long term effect of the strategic decisions is considered.

Therefore, we applied all the algorithms for each of the problem instances, and based our analysis on the best solutions obtained.

Further Research Issues

Although we obtain solutions to the multi-item integrated inventory/location problem in reasonable times by the application of proposed heuristics, we still do not know how far the best solution generated is from the optimal solution. The results of the experiments suggest that the algorithms proposed provide improved solutions with respect to the *p*-median solution, and therefore they are useful particularly in the absence of any efficient exact optimization methods. In order to evaluate the effectiveness of the heuristic algorithms for the multi-item integrated location/inventory problem on a more sound basis, the development of a lower bound can be considered as a future research study.

Further study might also include the generation of some special cases that will allow us to solve the problem optimally in an integrated way. For example, it may be possible to develop optimal solution procedures for the non-linear integer programming model if we can handle the joint replenishment problem in a different way so that determination of the base items does not require the evaluation of the setup cost/sales volume ($) ratio. We come across with some studies that mention about the closeness of the item groupings of the joint replenishment problem and that of the ABC analysis (Chakravarty, 1981; Chakravarty, 1985). Then according to the suggested grouping scheme, the base items may be determined *a priori*, not simultaneously with other decisions in the solution algorithm, which would probably simplify the development of solution procedures for the multi-item integrated location/inventory problem.

In this study, it is assumed that the decisions about the distribution strategy are already made such that the shipments of the items from the single supplier to the retailers are performed via distribution centers. The decisions about the distribution strategies can also be incorporated into the multi-item integrated location/allocation model as a future research study. For example, making direct shipments from the supplier to the retailers can be considered as an alternative distribution strategy. Then the model also finds the most appropriate distribution strategy between the supplier and retailers while making location/allocation decisions.

Integration of the inventory and location/allocation decisions may be extended to some other cases in different problem environments. For instance, there may be capacity restrictions at the distribution centers, which will necessitate the removal of the single source constraints. Also, the inventory maintained both at the plants and/or the retailers can also be considered and hence multi-echelon inventory control policies may be incorporated into the model. However, these extensions may increase the complexity of the problem more and therefore necessitate the development of more sophisticated solution techniques. Therefore, approximation and simplification methods should always be taken into consideration while making these extensions.

Although the heuristic algorithms developed in this study give solutions in reasonable times, they cannot guarantee optimality. The algorithms may terminate when a local minimum solution is obtained. In order to extend the exploration of the possible solutions to escape from local optima, suitable metaheuristic approaches can be investigated and applied for the multi-item integrated location/inventory problem as a future research study.

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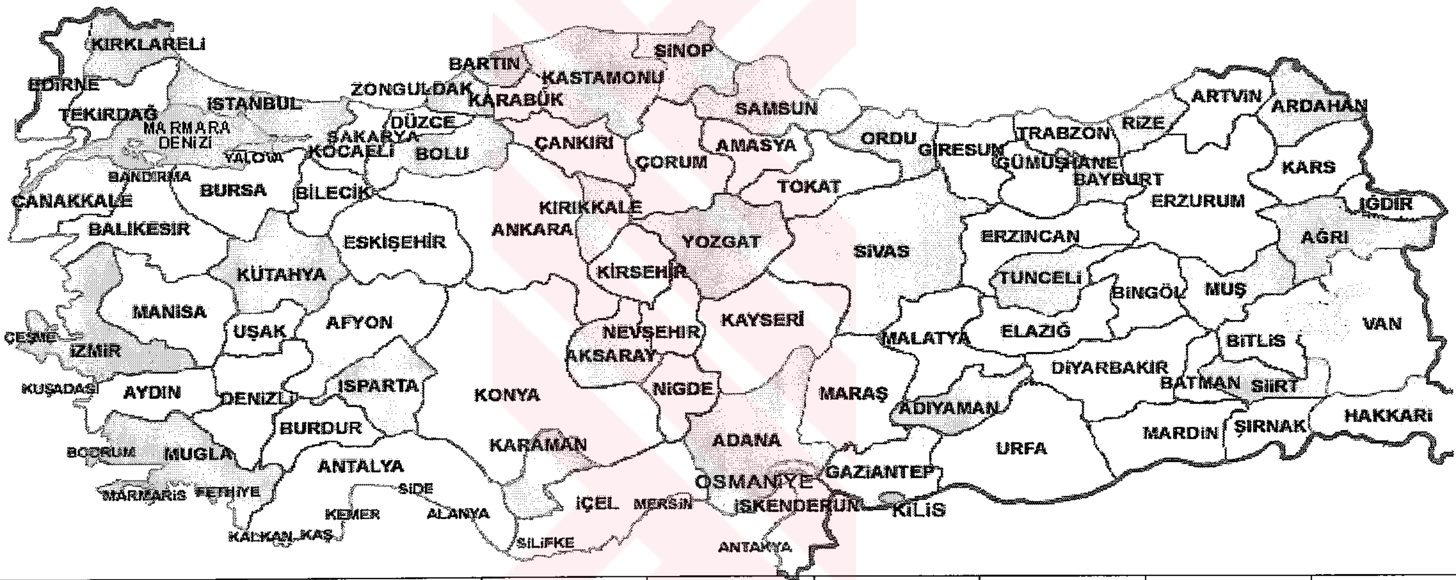
APPENDIX A

REPRESENTATION OF THE 81-CITY NETWORK



01. ADANA	10. BALIKESİR	19. ÇORUM	28. GİRESUN	37. KASTAMONU	46. K.MARAŞ	55. SAMSUN	64. UŞAK	73. ŞIRNAK
02. ADIYAMAN	11. BİLECİK	20. DENİZLİ	29. GÜMÜŞHANE	38. KAYSERİ	47. MARDİN	56. SİİRT	65. VAN	74. BARTIN
03. AFYON	12. BİNGÖL	21. DİYARBAKIR	30. HAKKARİ	39. KIRKLARELİ	48. MUĞLA	57. SİNOP	66. YOZGAT	75. ARDAHAN
04. AĞRI	13. BİTLİS	22. EDİRNE	31. HATAY	40. KIRŞEHİR	49. MUŞ	58. SİVAS	67. ZONGULDAK	76. IĞDIR
05. AMASYA	14. BOLU	23. ELAZIĞ	32. ISPARTA	41. KOCAELİ	50. NEVŞEHİR	59. TEKİRDAĞ	68. AKSARAY	77. YALOVA
06. ANKARA	15. BURDUR	24. ERZİNCAN	33. İÇEL	42. KONYA	51. NİĞDE	60. TOKAT	69. BAYBURT	78. KARABÜK
07. ANTALYA	16. BURSA	25. ERZURUM	34. İSTANBUL	43. KÜTAHYA	52. ORDU	61. TRABZON	70. KARAMAN	79. KİLİS
08. ARTVİN	17. ÇANAKKALE	26. ESKİŞEHİR	35. İZMİR	44. MALATYA	53. RİZE	62. TUNCELİ	71. KIRIKKALE	80. OSMANİYE
09. AYDIN	18. ÇANKIRI	27. G.ANTEP	36. KARS	45. MANİSA	54. SAKARYA	63. Ş.URFA	72. BATMAN	81. DÜZCE

Figure A.1: Position of the Retailers and their Respective Codes

APPENDIX B

DISTANCE MATRIX

Table B.1: Distance Matrix

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
1		333	573	972	612	490	556	1016	893	896	768	637	736	677	671	837	1106	576	572	767	526	1167	493	674	813	688	209
2	333		906	652	636	756	889	734	1226	1229	1059	351	416	947	1004	1128	1399	785	700	1100	206	1437	286	549	531	979	148
3	573	906		1315	593	257	288	1256	347	323	206	1130	1309	422	166	275	533	388	501	221	1099	684	986	946	1134	146	782
4	972	652	1315		735	1058	1451	374	1662	1567	1360	362	236	1144	1451	1416	1687	983	827	1536	446	1634	502	369	183	1291	763
5	612	636	593	735		336	874	709	940	832	625	641	834	409	759	681	952	248	92	814	702	899	551	366	554	569	609
6	490	756	257	1058	336		545	999	604	533	313	905	1098	191	423	382	653	131	244	478	912	681	761	689	877	233	672
7	556	889	288	1451	874	545		1465	343	509	474	1193	1292	690	122	543	719	676	782	221	1082	918	1049	1082	1270	430	765
8	1016	734	1256	374	709	999	1465		1603	1478	1271	383	520	1055	1422	1327	1598	911	755	1477	528	1545	523	383	203	1232	845
9	893	1226	347	1662	940	604	343	1603		293	525	1450	1629	714	272	442	449	735	848	126	1419	664	1306	1293	1481	489	1102
10	896	1229	323	1567	832	533	509	1478	293		245	1428	1621	423	396	151	210	658	775	288	1422	411	1284	1198	1386	300	1105
11	768	1059	206	1360	625	313	474	1271	525	245		1208	1401	216	352	94	365	444	557	399	1215	478	1064	991	1179	80	975
12	637	351	1130	362	641	905	1193	383	1450	1428	1208		197	1050	1228	1277	1548	889	733	1324	145	1540	144	275	180	1128	462
13	736	416	1309	236	834	1098	1292	520	1629	1621	1401	197		1243	1407	1470	1741	1082	926	1503	210	1733	337	468	329	1321	527
14	677	947	422	1144	409	191	690	1055	714	423	216	1050	1243		568	272	543	235	352	615	1103	490	952	775	963	296	863
15	671	1004	166	1451	759	423	122	1422	272	396	352	1228	1407	568		421	606	554	667	150	1197	805	1084	1082	1270	308	880
16	837	1128	275	1416	681	382	543	1327	442	151	94	1277	1470	272	421		271	507	624	437	1284	420	1133	1047	1235	149	1044
17	1106	1399	533	1687	952	653	719	1598	449	210	365	1548	1741	543	606	271		778	895	498	1555	217	1404	1318	1506	420	1315
18	576	785	388	983	248	131	676	911	735	658	444	889	1082	235	554	507	778		156	609	922	725	771	614	802	364	701
19	572	700	501	827	92	244	782	755	848	775	557	733	926	352	667	624	895	156		722	766	842	615	458	646	477	630
20	767	1100	221	1536	814	478	221	1477	126	288	399	1324	1503	615	150	437	498	609	722		1293	697	1180	1167	1355	363	976
21	526	206	1099	446	702	912	1082	528	1419	1422	1215	145	210	1103	1197	1284	1555	922	766	1293		1593	151	406	325	1135	317
22	1167	1437	684	1634	899	681	918	1545	664	411	478	1540	1733	490	805	420	217	725	842	697	1593		1442	1265	1453	558	1353
23	493	286	986	502	551	761	1049	523	1306	1284	1064	144	337	952	1084	1133	1404	771	615	1180	151	1442		263	320	984	348
24	674	549	946	369	366	689	1082	383	1293	1198	991	275	468	775	1082	1047	1318	614	458	1167	406	1265	263		188	922	611
25	813	531	1134	183	554	877	1270	203	1481	1386	1179	180	329	963	1270	1235	1506	802	646	1355	325	1453	320	188		1110	642
26	688	979	146	1291	569	233	430	1232	489	300	80	1128	1321	296	308	149	420	364	477	363	1135	558	984	922	1110		895
27	209	148	782	763	609	672	765	845	1102	1105	975	462	527	863	880	1044	1315	701	630	976	317	1353	348	611	642	895	

	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54
1	775	799	1077	192	620	69	939	896	1016	690	333	1148	374	828	356	669	392	878	188	533	869	747	285	205	731	974	791
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36	775	509	943	635	1558	694	431	443	708	1447	363	859	1241	1008	326	1146	1001	547	606	1189	91	138	1380	1119	913	929	1209
37	312	1141	194	475	639	367	658	749	952	614	1222	296	270	425	714	614	220	1054	1238	181	998	1099	461	111	875	777	290
38	452	779	589	194	904	264	665	570	490	656	919	175	587	179	574	317	246	692	856	602	863	920	726	534	413	374	555
39	946	1760	910	1102	118	994	1292	1376	1471	650	1849	881	540	883	1341	990	739	1673	1837	629	1632	1726	385	605	1394	1235	426
40	391	913	522	328	770	319	733	704	624	544	1053	112	453	109	708	320	112	826	990	468	997	1054	592	400	547	461	421
41	626	1440	590	782	243	674	972	1056	1151	390	1529	561	220	563	1021	670	419	1353	1517	309	1312	1406	65	285	1074	915	106
42	642	1064	697	521	800	561	975	897	702	335	1246	369	522	148	901	119	300	977	1068	537	1190	1247	544	469	602	443	490
43	730	1377	750	754	492	710	1076	1130	1015	141	1539	530	395	461	1108	432	388	1290	1381	484	1416	1480	236	460	915	756	281
44	587	438	737	247	1245	355	609	234	268	997	578	471	928	520	495	658	587	351	535	903	664	715	1067	833	307	305	896
45	981	1586	997	1005	516	961	1327	1381	1224	193	1768	781	627	670	1359	641	639	1499	1590	716	1667	1731	355	692	1124	965	513
46	647	552	797	345	1177	415	816	457	217	873	748	448	860	452	718	478	519	465	583	875	887	917	999	807	140	101	828
47	916	225	1066	576	1581	684	724	372	187	1218	451	800	1264	798	546	823	923	148	203	1232	664	620	1403	1162	392	446	1232
48	1043	1577	1063	1067	736	1023	1389	1443	1215	298	1773	843	830	705	1421	664	701	1490	1581	884	1729	1793	612	816	1115	956	716
49	818	180	986	583	1554	690	547	255	439	1352	223	807	1237	875	369	1013	942	218	277	1185	420	392	1376	1115	644	660	1205
50	466	883	603	298	861	338	752	674	594	552	1023	189	544	75	678	269	203	796	960	559	967	1024	683	491	517	372	512
51	542	907	679	322	927	392	793	698	551	584	1047	265	610	121	702	189	283	820	917	625	991	1048	749	557	451	292	578
52	165	833	333	341	1034	233	181	453	838	953	824	440	717	646	284	814	507	786	930	658	521	701	856	588	788	749	685
53	421	768	589	546	1290	489	75	450	859	1209	713	696	973	902	253	1057	763	731	865	914	265	488	1112	844	991	989	941
54	589	1403	553	745	280	637	935	1019	1114	353	1492	524	183	526	984	633	382	1316	1480	272	1275	1369	102	248	1037	878	69
55		998	168	340	869	232	346	575	837	788	989	279	552	500	449	711	342	917	1095	493	686	866	691	423	787	748	520
56	998		1156	666	1683	774	727	429	362	1393	265	890	1366	958	549	998	1025	87	97	1322	600	434	1505	1252	567	621	1334

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
55	730	754	676	755	131	419	957	580	1023	898	691	720	901	475	842	747	1018	331	175	897	820	965	669	445	574	652	727
56	708	388	1281	333	888	1098	1264	617	1601	1604	1401	284	97	1289	1379	1470	1741	1108	952	1475	186	1779	337	559	426	1321	499
57	880	904	696	923	268	439	984	748	1043	862	655	878	1069	439	862	711	982	308	312	917	970	929	819	603	742	672	877
58	428	414	700	615	222	443	836	629	1047	976	756	473	666	631	836	825	1096	442	286	921	480	1121	329	246	434	676	425
59	1071	1341	588	1538	803	585	856	1449	635	382	382	1444	1637	394	734	375	188	629	746	668	1497	137	1346	1169	1357	462	1257
60	498	522	656	674	114	399	876	648	1003	932	712	580	773	523	822	781	1052	334	178	877	588	1013	437	305	493	632	495
61	899	794	1022	484	475	765	1290	234	1369	1244	1037	483	630	821	1188	1093	1364	677	521	1243	628	1311	508	245	303	998	856
62	626	419	1076	423	496	819	1182	437	1423	1328	1121	145	338	905	1212	1177	1448	744	588	1297	276	1395	133	130	242	1052	481
63	346	109	919	626	719	809	902	708	1239	1242	1112	325	390	1000	1017	1181	1452	838	767	1113	180	1490	331	586	505	1032	137
64	685	1018	112	1427	705	369	294	1368	278	224	251	1242	1421	467	172	310	434	500	613	152	1211	633	1098	1058	1246	219	894
65	904	584	1463	234	969	1238	1460	562	1783	1761	1541	337	168	1378	1561	1610	1881	1217	1061	1657	378	1868	477	603	417	1461	695
66	470	612	476	839	196	219	684	853	823	752	532	697	890	410	642	601	872	248	104	697	704	900	553	470	658	452	528
67	754	1024	491	1221	486	268	759	1132	783	492	285	1127	1320	159	637	341	612	312	429	684	1180	559	1029	852	1040	365	940
68	265	598	365	988	417	225	463	1002	685	688	523	765	958	412	463	592	863	311	325	559	772	902	621	619	807	443	474
69	808	656	1054	306	461	797	1216	320	1401	1293	1086	305	452	870	1216	1142	1413	709	553	1275	450	1360	394	154	125	1030	742
70	290	623	336	1126	627	369	377	1140	648	659	531	903	1026	556	422	600	869	500	536	522	816	1009	759	757	945	451	499
71	474	683	334	981	259	77	615	922	681	610	390	832	1025	268	500	459	730	106	167	555	839	758	688	612	800	310	599
72	621	301	1194	371	801	1011	1177	580	1514	1517	1314	197	135	1202	1292	1383	1654	1021	865	1388	99	1692	250	472	377	1234	412
73	712	475	1285	430	985	1175	1268	714	1605	1608	1478	381	194	1366	1383	1547	1818	1204	1049	1479	283	1856	434	656	523	1398	503
74	769	1039	517	1169	434	283	805	1073	864	581	374	1075	1268	174	683	430	701	279	377	738	1136	648	985	800	988	454	955
75	1056	774	1362	307	789	1105	1505	114	1709	1584	1377	423	503	1161	1505	1433	1704	1017	861	1583	568	1651	563	423	243	1338	885
76	1073	753	1426	144	846	1169	1562	337	1773	1678	1471	474	337	1255	1562	1527	1798	1094	938	1647	547	1745	614	480	294	1402	864
77	893	1163	332	1360	625	407	600	1271	511	220	126	1266	1459	216	478	69	340	451	568	506	1319	404	1168	991	1179	206	1079
78	701	971	449	1099	364	215	737	1003	796	557	350	1005	1198	134	615	406	677	195	307	670	1066	624	915	730	918	425	887
79	246	216	819	831	669	732	802	913	1139	1142	1014	530	595	923	917	1083	1352	761	690	1013	385	1413	408	671	710	934	68
80	87	246	660	885	630	577	643	929	980	983	855	550	649	764	758	924	1193	663	651	854	439	1254	406	669	726	775	122
81	722	992	377	1189	454	236	645	1100	669	378	171	1095	1288	45	523	227	498	280	397	570	1148	445	997	820	1008	251	908

	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54
55	209	371	1192	823	841	740	737	999	775	312	452	946	391	626	642	730	587	981	647	916	1043	818	466	542	165	421	589
56	789	627	438	696	1328	777	1551	1604	509	1141	779	1760	913	1440	1064	1377	438	1586	552	225	1577	180	883	907	833	768	1403
57	377	539	1360	973	861	877	701	1019	943	194	589	910	522	590	697	750	737	997	797	1066	1063	986	603	679	333	589	553
58	385	371	979	521	785	497	893	1023	635	475	194	1102	328	782	521	754	247	1005	345	576	1067	583	298	322	341	546	745
59	1078	1240	1950	1263	733	1064	132	505	1558	639	904	118	770	243	800	492	1245	516	1177	1581	736	1554	861	927	1034	1290	280
60	277	391	1086	591	818	567	785	979	694	367	264	994	319	674	561	710	355	961	415	684	1023	690	338	392	233	489	637
61	137	100	921	989	1187	968	1083	1345	431	658	665	1292	733	972	975	1076	609	1327	816	724	1389	547	752	793	181	75	935
62	428	275	651	614	1161	695	1167	1399	443	749	570	1376	704	1056	897	1130	234	1381	457	372	1443	255	674	698	453	450	1019
63	870	708	731	334	966	415	1262	1242	708	952	490	1471	624	1151	702	1015	268	1224	217	187	1215	439	594	551	838	859	1114
64	997	1157	1748	877	171	678	501	211	1447	614	656	650	544	390	335	141	997	193	873	1218	298	1352	552	584	953	1209	353
65	780	618	203	892	1510	973	1640	1786	363	1222	919	1849	1053	1529	1246	1539	578	1768	748	451	1773	223	1023	1047	824	713	1492
66	484	595	1203	624	611	463	672	799	859	296	175	881	112	561	369	530	471	781	448	800	843	807	189	265	440	696	524
67	761	923	1633	946	636	747	331	663	1241	270	587	540	453	220	522	395	928	627	860	1264	830	1237	544	610	717	973	183
68	690	744	1271	457	412	258	674	688	1008	425	179	883	109	563	148	461	520	670	452	798	705	875	75	121	646	902	526
69	240	78	743	875	1165	877	1132	1377	326	714	574	1341	708	1021	901	1108	495	1359	718	546	1421	369	678	702	284	253	984
70	858	882	1367	482	371	236	781	659	1146	614	317	990	320	670	119	432	658	641	478	823	664	1013	269	189	814	1057	633
71	551	711	1338	666	499	467	530	657	1001	220	246	739	112	419	300	388	587	639	519	923	701	942	203	283	507	763	382
72	742	580	476	609	1241	690	1464	1517	547	1054	692	1673	826	1353	977	1290	351	1499	465	148	1490	218	796	820	786	731	1316
73	886	724	139	700	1332	781	1628	1608	606	1238	856	1837	990	1517	1068	1381	535	1590	583	203	1581	277	960	917	930	865	1480
74	702	864	1581	961	682	762	420	752	1189	181	602	629	468	309	537	484	903	716	875	1232	884	1185	559	625	658	914	272
75	477	438	651	1044	1454	1125	1423	1685	91	998	863	1632	997	1312	1190	1416	664	1667	887	664	1729	420	967	991	521	265	1275
76	657	495	428	1061	1511	1142	1517	1749	138	1099	920	1726	1054	1406	1247	1480	715	1731	917	620	1793	392	1024	1048	701	488	1369
77	900	1062	1772	1085	477	886	176	391	1380	461	726	385	592	65	544	236	1067	355	999	1403	612	1376	683	749	856	1112	102
78	632	794	1511	893	614	694	396	728	1119	111	534	605	400	285	469	460	833	692	807	1162	816	1115	491	557	588	844	248
79	832	816	936	148	866	315	1185	1142	913	875	413	1394	547	1074	602	915	307	1124	140	392	1115	644	517	451	788	991	1037
80	793	814	990	128	707	156	1026	983	929	777	374	1235	461	915	443	756	305	965	101	446	956	660	372	292	749	989	878
81	729	891	1601	914	522	715	217	549	1209	290	555	426	421	106	490	281	896	513	828	1232	716	1205	512	578	685	941	69

	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81
55		998	168	340	869	232	346	575	837	788	989	279	552	500	449	711	342	917	1095	493	686	866	691	423	787	748	520
56	998		1156	666	1683	774	727	429	362	1393	265	890	1366	958	549	998	1025	87	97	1322	600	434	1505	1252	567	621	1334
57	168	1156		490	833	382	514	733	987	808	1157	416	464	619	617	808	414	1069	1253	375	854	1034	655	305	937	898	484
58	340	666	490		1025	108	471	376	497	812	806	224	708	373	380	511	366	579	763	656	669	726	847	586	485	446	676
59	869	1683	833	1025		917	1215	1299	1394	604	1772	804	463	806	1264	913	662	1596	1760	552	1555	1649	308	528	1317	1158	349
60	232	774	382	108	917		414	435	605	768	908	207	600	413	400	581	322	687	871	548	728	785	739	478	555	516	568
61	346	727	514	471	1215	414		375	808	1134	718	621	898	827	178	982	688	680	824	839	340	563	1037	769	916	914	866
62	575	429	733	376	1299	435	375		456	1188	478	600	982	749	261	887	742	342	526	930	477	534	1121	860	541	539	950
63	837	362	987	497	1394	605	808	456		1031	558	665	1077	611	630	636	736	275	366	1092	748	727	1216	1024	205	259	1045
64	788	1393	808	812	604	768	1134	1188	1031		1575	588	536	477	1166	448	446	1306	1397	625	1474	1538	377	561	931	772	422
65	989	265	1157	806	1772	908	718	478	558	1575		1030	1455	1098	540	1194	1165	303	362	1403	448	225	1594	1333	763	817	1423
66	279	890	416	224	804	207	621	600	665	588	1030		487	221	604	432	142	803	987	477	893	950	626	407	588	549	455
67	552	1366	464	708	463	600	898	982	1077	536	1455	487		489	947	633	345	1279	1443	89	1238	1332	285	173	1000	841	114
68	500	958	619	373	806	413	827	749	611	477	1098	221	489		753	211	209	871	977	504	1042	1099	628	436	511	352	457
69	449	549	617	380	1264	400	178	261	630	1166	540	604	947	753		891	720	502	646	895	360	417	1086	825	802	800	915
70	711	998	808	511	913	581	982	887	636	448	1194	432	633	211	891		411	911	1002	648	1180	1237	657	580	536	377	601
71	342	1025	414	366	662	322	688	742	736	446	1165	142	345	209	720	411		938	1102	360	1028	1092	484	292	659	561	313
72	917	87	1069	579	1596	687	680	342	275	1306	303	803	1279	871	502	911	938		184	1235	620	472	1418	1165	480	534	1247
73	1095	97	1253	763	1760	871	824	526	366	1397	362	987	1443	977	646	1002	1102	184		1419	697	531	1582	1349	571	625	1411
74	493	1322	375	656	552	548	839	930	1092	625	1403	477	89	504	895	648	360	1235	1419		1179	1280	374	84	1015	856	203
75	686	600	854	669	1555	728	340	477	748	1474	448	893	1238	1042	360	1180	1028	620	697	1179		223	1377	1109	953	969	1206
76	866	434	1034	726	1649	785	563	534	727	1538	225	950	1332	1099	417	1237	1092	472	531	1280	223		1471	1210	932	986	1300
77	691	1505	655	847	308	739	1037	1121	1216	377	1594	626	285	628	1086	657	484	1418	1582	374	1377	1471		350	1139	980	171
78	423	1252	305	586	528	478	769	860	1024	561	1333	407	173	436	825	580	292	1165	1349	84	1109	1210	350		947	788	179
79	787	567	937	485	1317	555	916	541	205	931	763	588	1000	511	802	536	659	480	571	1015	953	932	1139	947		159	968
80	748	621	898	446	1158	516	914	539	259	772	817	549	841	352	800	377	561	534	625	856	969	986	980	788	159		809
81	520	1334	484	676	349	568	866	950	1045	422	1423	455	114	457	915	601	313	1247	1411	203	1206	1300	171	179	968	809	

APPENDIX C

THE RESULTS OF THE IMPROVEMENT TYPE ALGORITHM FOR THE SENSITIVITY ANALYSIS BASED ON THE TRANSPORTATION AND INVENTORY COSTS

Table C.1: Results Obtained by Improvement Type Algorithm for α = 0.5, β =0.5

	p-median					
p	Initial obj. func.	Obj. func. (last)	rand	%impr	time (p)	time (rand)
1	1599955.681	1599955.681	1599955.681		0	0
2	1579313.003	1510925.877	1510499.046	%4.36	7	594
3	1528410.438	1491988.791	1462504.391	%4.31	7	473
4	1489055.510	1449357.310	1443000.502	%3.09	6	400
5*	1494384.177	1427825.284	1426721.332	%4.53	4	340
6	1515500.557	1461084.832	1451955.001	%4.19	3	284
7	1517852.624	1472287.678	1465036.231	%3.48		
8	1522227.948	1477536.143	1476069.054	%3.03		
9	1620375.109	1524315.307	1501434.806	%7.34		
10	1636824.526	1561666.182	1531608.422	%6.43		
11	1681354.997	1579948.894	1557663.097	%7.36		
12	1726319.140	1613304.807	1588587.648	%7.98		
13	1781238.444	1643552.064	1624974.068	%8.77		
14	1808964.662	1674457.495	1655895.939	%8.46		
15	1896354.976	1705431.526	1691406.991	%10.81		

Overall improvement with respect to p-median solution: %4.19

Computation time in seconds (p-median): 27
Computation time in seconds (random): 2091

													Cost composition (min. of p-med&rand)			
p	Opened DCs (p median)						Opened DCs (random)						shipping	fixed	safety	order+inv
1	6						6						1433270.955	135456.000	5388.529	25840.196
2	54	71					54	71					1381629.240	86729.000	7477.171	34663.636
3	3	54	71				54	71	80				1274577.135	135603.000	8665.805	43658.451
4	2	3	54	71			3	54	71	80			1173891.270	208611.000	10036.027	50462.205
5*	3	25	54	71	80		3	25	54	71	80		1112867.430	247081.000	10922.595	55850.308
6	3	12	28	33	54	71	3	12	33	38	54	71	1099575.975	279479.000	11850.949	61049.077

Table C.2: Results Obtained by Improvement Type Algorithm for $\alpha = 0.5$, $\beta = 1$

	p-median					
p	Initial obj. func.	Obj. func. (last)	rand	%impr	time (p)	time (rand)
1	1616047.570	1616047.570	1616047.570		0	0
2	1601684.847	1532937.995	1532334.365	%4.33	7	628
3	1555985.544	1518449.292	1489254.119	%4.29	7	497
4	1520823.899	1480644.775	1473938.659	%3.08	6	434
5*	1529419.195	1462218.392	1460680.420	%4.49	4	379
6	1553457.379	1498583.062	1489093.305	%4.14	3	298
7	1558369.808	1512127.612	1503357.929	%3.53		
8	1564973.682	1519848.187	1530446.471	%2.88		
9	1666816.578	1569751.326	1544861.951	%7.32		
10	1685389.843	1609652.669	1576550.358	%6.46		
11	1731893.968	1633774.298	1604340.617	%7.36		
12	1780104.752	1664839.036	1636591.133	%8.06		
13	1836553.780	1715505.999	1668736.074	%9.14		
14	1866015.814	1745100.269	1705686.981	%8.59		
15	1956014.352	1777680.442	1740994.463	%10.99		

Overall improvement with respect to p-median solution: %3.95

Computation time in seconds (p-median): 27
Computation time in seconds (random): 2236

													Cost composition (min. of p-med&rand)			
p	Opened DCs (p median)						Opened DCs (random)						shipping	fixed	safety	order+inv
1	6						6						1433270.955	135456.000	10777.059	36543.556
2	54	71					54	71					1381629.240	86729.000	14954.341	49021.783
3	3	54	71				54	71	80				1274577.135	135603.000	17331.611	61742.373
4	2	3	54	71			3	54	71	80			1173891.270	208611.000	20072.054	71364.335
5*	3	25	54	71	80		3	25	54	71	80		1113127.605	247081.000	21765.301	78706.514
6	3	12	28	33	54	71	3	12	33	38	54	71	1099575.975	279479.000	23701.897	86336.433

Table C.3: Results Obtained by Improvement Type Algorithm for $\alpha = 0.5$, $\beta = 2$

	p-median					
p	**Initial obj. func.**	**Obj. func. (last)**	**rand**	**%impr**	**time (p)**	**time (rand)**
1	1641961.465	1641961.465	1641961.465		0	0
2	1637469.876	1568447.856	1567594.194	%4.27	7	586
3	1600228.277	1561077.952	1532160.258	%4.25	7	522
4	1571982.222	1530956.868	1523570.788	%3.08	6	457
5*	1585592.291	1517222.047	1515047.026	%4.45	4	452
6	1614195.053	1558595.502	1548918.002	%4.04	3	374
7	1623127.094	1575831.715	1549624.674	%4.53		
8	1633229.033	1587428.983	1584494.805	%2.98		
9	1740880.481	1642265.599	1613951.883	%7.29		
10	1762769.371	1686218.099	1648345.715	%6.49		
11	1812348.814	1710681.785	1678841.218	%7.37		
12	1865855.581	1747038.712	1713156.466	%8.18		
13	1924498.843	1798921.234	1746786.809	%9.23		
14	1956737.344	1814724.276	1784179.954	%8.82		
15	2050787.589	1831850.794	1820346.319	%11.24		

Overall improvement with respect to p-median solution: %3.62

Computation time in seconds (p-median): 27
Computation time in seconds (random): 2391

													Cost composition (min. of p-med&rand)			
p	**Opened DCs (p median)**						**Opened DCs (random)**						**shipping**	**fixed**	**safety**	**order+inv**
1	6						6						1433270.955	135456.000	21554.118	51680.392
2	54	71					54	71					1381629.240	86729.000	29908.683	69327.271
3	3	54	71				54	71	80				1274577.135	135603.000	34663.222	87316.901
4	2	3	54	71			3	54	71	80			1173891.270	208611.000	40144.108	100924.410
5*	3	25	54	71	80		3	25	54	71	80		1113127.605	247081.000	43530.602	111307.819
6	3	12	28	33	54	71	3	25	33	38	54	71	1108229.115	272678.000	46606.518	121404.369

Table C.4: Results Obtained by Improvement Type Algorithm for $\alpha = 0.5$, $\beta = 5$

	p-median					
p	**Initial obj. func.**	**obj. func. (last)**	**rand**	**%impr**	**time (p)**	**time (rand)**
1	1704326.125	1704326.125	1704326.125		0	0
2	1722853.652	1654095.745	1652745.988	%4.07	7	572
3*	1706205.649	1663657.717	1634898.333	%4.18	8	704
4	1695098.759	1651294.873	1637765.508	%3.38	6	619
5	1720029.030	1648240.341	1644822.670	%4.37		
6	1759188.669	1701688.193	1680874.528	%4.45		
7	1777479.048	1727621.391	1699850.432	%4.37		
8	1795723.134	1748325.684	1744225.489	%2.87		
9	1916918.094	1811825.006	1779703.907	%7.16		
10	1946467.932	1848866.213	1816502.269	%6.68		
11	2003134.754	1886131.377	1847771.531	%7.76		
12	2067739.252	1943690.719	1885698.223	%8.80		
13	2133043.735	1988684.667	1928568.770	%9.59		
14	2171560.070	2020623.377	1966225.864	%9.46		
15	2274908.884	2045404.029	2005916.143	%11.82		

Overall improvement with respect to p-median solution: %3.55

Computation time in seconds (p-median): 21
Computation time in seconds (random): 1895

													Cost composition (min. of p-med&rand)			
p	Opened DCs (p median)						Opened DCs (random)						shipping	fixed	safety	order+inv
1	6						6						1433270.955	135456.000	53885.295	81713.875
2	54	71					54	71					1381629.240	86729.000	74771.707	109616.040
3*	3	54	71				54	71	80				1274577.135	135603.000	86658.055	138060.143
4	2	3	54	71			25	54	71	80			1214112.630	174073.000	95048.573	154531.305

Table C.5: Results Obtained by Improvement Type Algorithm for α = 0.5, β =7.5

	p-median					
p	**Initial obj. func.**	**Obj. func. (last)**	**rand**	**%Impr**	**time (p)**	**time (rand)**
1	1749633.546	1749633.546	1749633.546		0	0
2	1784486.255	1716420.593	1714767.484	%3.91	7	286
3*	1782928.536	1728497.250	1709255.669	%4.13	7	449
4	1784541.046	1738499.981	1720019.912	%3.62	6	423
5	1817291.096	1742636.454	1738450.679	%4.34		
6	1863888.880	1797074.454	1775888.369	%4.72		
7	1888807.701	1829330.578	1817044.752	%3.80		
8	1912817.726	1863788.030	1854124.190	%3.07		
9	2043616.746	1901307.481	1888704.830	%7.58		
10	2078560.177	1942599.232	1929957.678	%7.15		
11	2140206.468	1983419.632	1969486.371	%7.98		
12	2212358.788	2045949.818	2007598.524	%9.26		
13	2282869.322	2095847.576	2054902.801	%9.99		
14	2325728.205	2126248.237	2097196.291	%9.83		
15	2435588.034	2167068.637	2138699.616	%12.19		

Overall improvement with respect to p-median solution: %2.31

Computation time in seconds (p-median): 20
Computation time in seconds (random): 1158

													Cost composition (min. of p-med&rand)			
p	**Opened DCs (p median)**						**Opened DCs (random)**						**shipping**	**fixed**	**safety**	**order+inv**
1	6						6						1433270.955	135456.000	80827.942	100078.649
2	54	71					54	71					1381629.240	86729.000	112157.561	134251.683
3*	38	54	71				54	71	80				1274577.135	135603.000	129987.082	169088.452
4	2	3	54	71			25	54	71	80			1214112.630	174073.000	142572.859	189261.423

Table C.6: Results Obtained by Improvement Type Algorithm for α = 0.5, β = 12.5

	p-median					
p	**Initial obj. func.**	**Obj. func. (last)**	**rand**	**%impr**	**time (p)**	**time (rand)**
1	1832641.173	1832641.173	1832641.173		0	0
2*	1896881.963	1830739.840	1828605.686	%3.60	7	330
3*	1923140.324	1865580.367	1843346.160	%4.15	7	453
4	1948406.904	1898116.417	1870030.267	%4.02	6	437
5	1994954.140	1914635.107	1909258.778	%4.30		
6	2054876.372	1961288.157	1945066.310	%5.34		
7	2091716.105	2046089.253	1992958.275	%4.72		
8	2126094.419	2053118.941	2034464.879	%4.31		
9	2274181.011	2097103.495	2074809.123	%8.77		
10	2318780.749	2138819.078	2116030.546	%8.74		
11	2389327.999	2184246.352	2162725.173	%9.48		
12	2475257.024	2243561.332	2215172.805	%10.51		
13	2554906.335	2307365.994	2267555.566	%11.25		
14	2605435.374	2331481.882	2311747.306	%11.27		
15	2726904.061	2388813.516	2364686.214	%13.28		

Overall improvement with respect to p-median solution: %0.22

Computation time in seconds (p-median): 14
Computation time in seconds (random): 783

													Cost composition (min. of p-med&rand)			
p	**Opened DCs (p median)**						**Opened DCs (random)**						**shipping**	**fixed**	**safety**	**order+inv**
1	6						6						1433270.955	135456.000	134713.237	129200.980
2*	54	71					54	71					1381629.240	86729.000	186929.269	173318.178
3	38	54	71				12	54	71				1284914.610	132000.000	217378.083	209053.467

Table C.7: Results Obtained by Improvement Type Algorithm for $\alpha = 0.5$, $\beta = 25$

p	p-median		rand	%impr	time (p)	time (rand)
	Initial obj. func.	Obj. func. (last)				
1*	2020871.208	2020871.208	2020871.208		0	0
2	2150310.295	2097742.711	2065175.295	%3.96	9	203
3	2240113.400	2183548.946	2111033.808	%5.76		
4	2308107.532	2224159.368	2156996.449	%6.55		
5	2396358.406	2302323.929	2207942.662	%7.86		
6	2485656.871	2361459.087	2259357.188	%9.10		
7	2548911.360	2389934.565	2312059.794	%9.29		
8	2606259.971	2463972.326	2363433.300	%9.32		
9	2792695.711	2492638.966	2419600.978	%13.36		
10	2858568.736	2548282.070	2477689.673	%13.32		
11	2948685.744	2615225.819	2534536.108	%14.05		
12	3065712.203	2646493.639	2593208.780	%15.41		
13	3165820.253	2700095.722	2652021.949	%16.23		
14	3232951.183	2755873.424	2714894.195	%16.02		
15	3379858.741	2826368.849	2773926.279	%17.93		

Overall improvement with respect to p-median solution: %0.0

Computation time in seconds (p-median): 9
Computation time in seconds (random): 203

p	Opened DCs (p median)						Opened DCs (random)						Cost composition (min. of p-med&rand)			
													Shipping	fixed	safety	order+inv
1*	6						6						1433270.955	135456.000	269426.475	182717.779
2	6	38					6	76					1429492.162	169888.000	273964.867	191830.265

Table C.8: Results Obtained by Improvement Type Algorithm for $\alpha = 1$, $\beta = 0.5$

	p-median					
p	**Initial obj. func.**	**Obj. func. (last)**	**rand**	**%impr**	**time (p)**	**time (rand)**
1	3033226.636	3033226.636	3033226.636		0	0
2	2940877.043	2882686.147	2857007.428	%2.85	9	300
3	2810413.779	2741174.655	2725626.759	%3.02	7	369
4	2682136.325	2635649.778	2608559.018	%2.74	6	215
5*	2640308.510	2518500.529	2518500.529	%4.61	17	344
6	2640470.257	2519771.678	2519771.678	%4.57	3	265
7	2635921.875	2532816.397	2528887.920	%4.06		
8	2604657.665	2550739.183	2547897.067	%2.18		
9	2670235.412	2575596.716	2564427.131	%3.96		
10	2669310.346	2585817.697	2571626.949	%3.66		
11	2705385.467	2626705.066	2593352.812	%4.14		
12	2742274.554	2651390.472	2623666.018	%4.33		
13	2786329.493	2677824.429	2638556.385	%5.30		
14	2806828.168	2694735.542	2677098.104	%4.62		
15	2858619.642	2720984.516	2696554.483	%5.67		

Overall improvement with respect to p-median solution: %3.31

Computation time in seconds (p-median): 42
Computation time in seconds (random): 1493

													Cost composition (min. of p-med&rand)			
p	**Opened DCs (p median)**						**Opened DCs (random)**						**shipping**	**fixed**	**safety**	**order+inv**
1	6						6						2866541.910	135456.000	5388.529	25840.196
2	6	38					6	12					2629923.750	184330.000	6849.350	35904.328
3	6	38	54				1	6	12				2453955.960	219138.000	8988.028	43544.771
4	2	3	54	71			1	6	12	54			2256484.860	291154.000	9962.961	50957.197
5*	1	3	12	54	71		1	3	12	54	71		2173224.960	277024.000	11145.303	57106.266
6	1	3	12	28	54	71	1	3	12	28	54	71	2107851.810	338101.000	11931.135	61887.733

Table C.9: Results Obtained by Improvement Type Algorithm for $\alpha = 1$, $\beta = 1$

	p-median					
p	Initial obj. func.	Obj. func. (last)	rand	%impr	time (p)	time (rand)
1	3049318.525	3049318.525	3049318.525		0	0
2	2963248.887	2904335.032	2878728.838	%2.85	4	326
3	2838092.511	2768547.666	2752651.622	%3.01	4	355
4	2714194.855	2667121.307	2639629.141	%2.75	3	288
5*	2675368.875	2553300.023	2553300.023	%4.56	12	424
6	2678427.079	2557337.551	2557337.551	%4.52	2	244
7	2676800.023	2568799.707	2568799.707	%4.03		
8	2647764.362	2589165.899	2590094.593	%2.21		
9	2716500.417	2618814.864	2614170.312	%3.77		
10	2717875.663	2631232.117	2632040.900	%3.19		
11	2755924.438	2673692.370	2641593.525	%4.15		
12	2795366.582	2700332.423	2674921.372	%4.31		
13	2841316.718	2728642.416	2695400.564	%5.14		
14	2863434.727	2747583.327	2730039.875	%4.66		
15	2917834.425	2775176.910	2752285.819	%5.67		

Overall improvement with respect to p-median solution: %3.57

Computation time in seconds (p-median): 25
Computation time in seconds (random): 1637

													Cost composition (min. of p-med&rand)			
p	Opened DCs (p median)						Opened DCs (random)						shipping	fixed	safety	order+inv
1	6						6						2866541.910	135456.000	10777.059	36543.556
2	6	38					6	80					2629923.750	184330.000	13698.700	50776.388
3	6	38	54				6	12	54				2453955.960	219138.000	17976.056	61581.605
4	2	3	54	71			1	6	12	54			2256484.860	291154.000	19925.922	72064.359
5*	1	3	12	54	71		1	3	12	54	71		2173224.960	277024.000	22290.606	80760.456
6	1	3	12	28	54	71	1	3	12	28	54	71	2107851.810	338101.000	23862.269	87522.472

Table C.10: Results Obtained by Improvement Type Algorithm for $\alpha = 1, \beta = 2$

p	p-median Initial obj. func.	p-median Obj. func. (last)	rand	%impr	time (p)	time (rand)
1	3075232.420	3075232.420	3075232.420		0	0
2	2999033.916	2938913.560	2913459.806	%2.85	9	314
3	2882481.794	2812405.883	2796135.614	%3.00	7	361
4	2765763.501	2717567.246	2689405.099	%2.76	6	295
5*	2731577.818	2620778.659	2609042.705	%4.49	4	245
6	2739164.753	2617452.815	2617452.815	%4.44	3	208
7	2742067.789	2632612.851	2632612.851	%3.99		
8	2716530.193	2656794.048	2657987.685	%2.20		
9	2790314.764	2691360.997	2685381.663	%3.76		
10	2795255.191	2707261.850	2702769.664	%3.31		
11	2836379.284	2752096.811	2722173.851	%4.03		
12	2879943.239	2781733.289	2748062.052	%4.58		
13	2928897.711	2809549.628	2776642.599	%5.20		
14	2953527.509	2831619.850	2804929.302	%5.03		
15	3011978.913	2861302.246	2840125.873	%5.71		

Overall improvement with respect to p-median solution: %3.96

Computation time in seconds (p-median): 29
Computation time in seconds (random): 1423

													Cost composition (min. of p-med&rand)			
p	Opened DCs (p median)						Opened DCs (random)						shipping	fixed	safety	order+inv
1	6						6						2866541.910	135456.000	21554.118	51680.392
2	6	38					6	80					2629923.750	184330.000	27397.400	71808.656
3	6	38	54				6	12	54				2453955.960	219138.000	35952.113	87089.542
4	2	3	54	71			1	6	12	54			2256484.860	291154.000	39851.845	101914.394
5*	1	3	12	54	71		1	3	12	54	71		2173224.960	277024.000	44581.213	114212.532
6	1	3	12	28	54	71	1	3	12	28	54	71	2107851.810	338101.000	47724.539	123775.467

Table C.11: Results Obtained by Improvement Type Algorithm for $\alpha = 1, \beta = 5$

	p-median					
p	**initial obj. func.**	**obj. func. (last)**	**rand**	**%impr**	**time (p)**	**time (rand)**
1	3137597.080	3137597.080	3137597.080		0	0
2	3084417.692	3021265.009	2996286.705	%2.86	9	309
3	2988749.940	2917277.953	2892322.338	%3.23	8	317
4	2889694.171	2838631.003	2808409.277	%2.81	6	269
5*	2866085.681	2751956.501	2742287.862	%4.32	4	260
6	2883750.744	2760970.353	2760970.353	%4.26	3	275
7	2897024.978	2784786.349	2794103.293	%3.87		
8	2880037.153	2817783.931	2817957.179	%2.16		
9	2965857.223	2863895.022	2848458.613	%3.96		
10	2978953.752	2900298.305	2880110.487	%3.32		
11	3027165.224	2917844.422	2903847.456	%4.07		
12	3080680.589	2957340.440	2939168.236	%4.59		
13	3136720.241	2991775.431	2961974.955	%5.57		
14	3167102.714	3020865.929	3001179.763	%5.24		
15	3234852.688	3068677.329	3034744.989	%6.19		

Overall improvement with respect to p-median solution: %4.78

Computation time in seconds (p-median): 30
Computation time in seconds (random): 1430

													Cost composition (min. of p-med&rand)			
p	**Opened DCs (p median)**						**Opened DCs (random)**						**shipping**	**fixed**	**safety**	**order+inv**
1	6						6						2866541.910	135456.000	53885.295	81713.875
2	6	38					6	80					2629923.750	184330.000	68493.500	113539.455
3	6	38	54				6	54	80				2439041.760	222741.000	88400.407	142139.171
4	2	3	54	71			1	6	12	54			2256484.860	291154.000	99629.612	161140.805
5*	1	3	12	54	71		1	3	12	54	71		2173224.960	277024.000	111453.032	180585.870
6	1	3	12	28	54	71	1	3	12	28	54	71	2107851.810	338101.000	119311.347	195706.196

Table C.12: Results Obtained by Improvement Type Algorithm for $\alpha = 1$, $\beta = 15$

	p-median					
p	initial obj. func.	Obj. func. (last)	rand	%impr	time (p)	time (rand)
1	3305186.378	3305186.378	3305186.378		0	0
2	3311458.168	3239691.270	3214318.615	%2.93	9	320
3	3272490.965	3196881.917	3170123.271	%3.13	9	706
4	3222155.021	3136372.334	3125631.758	%3.00	6	621
5*	3225042.237	3100288.204	3097000.939	%3.97	5	486
6	3268136.171	3158581.255	3133382.454	%4.12	4	428
7	3307546.007	3205371.820	3172202.136	%4.09		
8	3312934.989	3244639.247	3226247.219	%2.62		
9	3430724.032	3312048.779	3272602.994	%4.61		
10	3464353.384	3350796.050	3303592.064	%4.64		
11	3530585.685	3411386.121	3359998.543	%4.83		
12	3606688.005	3417686.612	3406491.748	%5.55		
13	3681293.373	3471274.300	3454138.000	%6.17		
14	3726180.189	3533831.471	3503116.299	%5.99		
15	3817440.284	3578105.906	3546465.378	%7.10		

Overall improvement with respect to p-median solution: %3.88

Computation time in seconds (p-median): 33
Computation time in seconds (random): 2561

													Cost composition (min. of p-med&rand)			
p	Opened DCs (p median)						Opened DCs (random)						shipping	fixed	safety	order+inv
1	6						6						2866541.910	135456.000	161655.885	141532.583
2	6	38					6	12					2648514.000	180727.000	200452.951	184624.664
3	6	38	54				1	6	12				2447366.850	252743.000	239708.904	230304.517
4	1	3	54	71			1	6	12	54			2256484.860	291154.000	298888.836	279104.062
5*	1	3	25	54	71		1	3	12	54	71		2174144.760	277024.000	333404.699	312427.479
6	1	3	12	54	60	71	1	3	25	54	56	71	2168058.945	302726.000	336227.550	326369.959

Table C.13: Results Obtained by Improvement Type Algorithm for $\alpha = 1$, $\beta = 25$

p	p-median Initial obj. func.	p-median Obj. func. (last)	rand	%impr	time (p)	time (rand)
1	3454142.163	3454142.163	3454142.163		0	0
2	3511874.335	3432081.148	3401678.668	%3.14	9	322
3*	3523635.575	3444117.606	3394182.290	%3.67	4	664
4	3512691.337	3417400.400	3403558.482	%3.11	6	602
5	3542654.249	3407228.369	3407228.369	%3.82		
6	3607855.949	3492236.849	3449919.945	%3.20		
7	3669500.583	3559321.361	3497156.870	%4.70		
8	3693980.282	3620727.735	3540924.461	%4.14		
9	3839969.617	3663344.166	3593165.241	%6.43		
10	3891054.556	3710487.434	3639002.559	%6.48		
11	3972716.214	3759155.958	3697284.941	%6.93		
12	4064145.006	3799002.697	3757593.047	%7.54		
13	4154979.992	3846002.886	3805620.175	%8.41		
14	4212210.929	3887065.106	3861031.430	%8.34		
15	4323519.647	3947428.186	3925528.746	%9.21		

Overall improvement with respect to p-median solution: %3.37

Computation time in seconds (p-median): 19
Computation time in seconds (random): 1588

p	Opened DCs (p median)						Opened DCs (random)						Cost composition (min. of p-med&rand) shipping	fixed	safety	order+inv
1	6						6						2866541.910	135456.000	269426.475	182717.779
2	6	38					6	12					2648514.000	180727.000	334088.252	238349.416
3*	6	38	54				1	6	25				2471415.210	245942.000	385212.070	291613.010
4	1	3	54	71			1	6	25	54			2279467.860	284353.000	484353.472	355384.150

Table C.14: Results Obtained by Improvement Type Algorithm for $\alpha = 1$, $\beta = 50$

	p-median					
p	Initial obj. func.	Obj. func. (last)	rand	%impr	time (p)	time (rand)
1*	3799252.820	3799252.820	3799252.820		0	0
2	3973937.700	3874465.904	3834321.715	%3.51	10	208
3	4103777.093	4014627.875	3886068.807	%5.31		
4	4160589.175	4072376.127	3940690.175	%5.29		
5	4275646.366	4178269.413	3997724.219	%6.50		
6	4391766.451	4183827.384	4056182.425	%7.64		
7	4501305.284	4232035.629	4115559.739	%8.57		
8	4568206.260	4266899.220	4177076.555	%8.56		
9	4781161.268	4335139.655	4255850.152	%10.99		
10	4871380.205	4405430.605	4308985.776	%11.54		
11	4988316.226	4475629.040	4376925.738	%12.26		
12	5113918.509	4602976.551	4446149.247	%13.06		
13	5241907.578	4582375.499	4517770.643	%13.81		
14	5326836.330	4652573.934	4586347.118	%13.90		
15	5483199.089	4722349.236	4661282.781	%14.99		

Overall improvement with respect to p-median solution: %0.0

Computation time in seconds (p-median): 10
Computation time in seconds (random): 208

													Cost composition (min. of p-med&rand)			
p	Opened DCs (p median)						Opened DCs (random)						shipping	fixed	safety	order+inv
1*	6						6						2866541.910	135456.000	538852.949	258401.961
2	6	38					6	12					2648870.685	180727.000	668049.178	336674.852

Table C.15: Results Obtained by Improvement Type Algorithm for $\alpha = 2$, $\beta = 0.5$

	p-median					
p	Initial obj. func.	Obj. func. (last)	rand	%impr	time (p)	time (rand)
1	5899768.546	5899768.546	5899768.546		0	0
2	5664005.123	5548924.297	5467635.801	%3.47	9	301
3	5354509.299	5216530.815	5198705.300	%2.91	7	261
4	5050708.437	4988687.922	4866604.933	%3.65	6	242
5	4845692.245	4710231.695	4693939.003	%3.13	5	216
6	4785553.039	4625836.242	4616502.407	%3.53	11	186
7	4748104.353	4566863.109	4569352.201	%3.76	11	181
8	4667583.618	4531579.727	4555250.997	%2.91	3	190
9	4742747.922	4544246.544	4534698.851	%4.39	3	190
10*	4717230.701	4562462.139	4520597.647	%4.17	8	176
11	4716405.020	4567060.710	4538418.601	%3.77	2	175
12	4695733.881	4608294.103	4543691.016	%3.24		
13	4716785.793	4620773.159	4547485.897	%3.59		
14	4718243.963	4624300.303	4568793.557	%3.17		
15	4712872.495	4611261.638	4564004.345	%3.16		

Overall improvement with respect to p-median solution: %3.15

Computation time in seconds (p-median): 65
Computation time in seconds (random): 2118

p	Opened DCs (p median)											Opened DCs (random)										
1	6											6										
2	6	38										1	6									
3	6	38	54									1	6	12								
4	3	6	44	54								1	6	12	54							
5	1	6	12	54	64							1	3	12	54	71						
6	1	6	12	28	54	64						1	6	12	28	45	54					
7	1	6	12	28	32	45	54					1	6	12	28	32	45	54				
8	1	6	21	25	32	45	54	55				1	6	12	28	32	34	45	54			
9	1	21	25	26	28	32	45	54	71			1	2	6	25	32	38	45	54	55		
10*	1	6	21	25	26	31	32	45	54	55		1	2	6	25	32	34	38	45	54	55	
11	1	2	25	26	28	32	38	42	45	54	71	1	6	21	25	28	32	34	38	45	54	71

	Cost composition (min.of p-med&rand)			
p	shipping	fixed	safety	order+inv
1	5733083.820	135456.000	5388.529	25840.196
2	5217028.080	207472.000	6849.350	36286.371
3	4894733.700	252743.000	7990.297	43238.303
4	4512969.720	291154.000	9962.961	52518.252
5	4346449.920	277024.000	11145.303	59319.780
6	4112645.070	427280.000	11886.435	64690.902
7	4015791.090	471340.000	12556.761	69664.350
8	3901208.490	546861.000	12963.699	70546.537
9	3883388.790	559001.000	13709.244	78599.817
10*	3744957.450	676570.000	14638.498	84431.699
11	3698576.760	737144.000	15104.931	87592.910

Table C.16: Results Obtained by Improvement Type Algorithm for $\alpha = 2$, $\beta = 1$

	p-median						
p	**Initial obj. func.**	**Obj. func. (last)**	**rand**	**%impr**	**time(p)**	**time(rand)**
1	5915860.435	5915860.435	5915860.435		0	0
2	5686376.967	5570573.182	5489515.458	%3.46	9	301
3	5382188.031	5243903.826	5224605.488	%2.93	8	281
4	5083131.021	5020799.542	4898321.666	%3.64	6	242
5	4880978.553	4745242.120	4729655.364	%3.10	5	230
6	4823637.183	4663618.523	4655184.691	%3.49	11	186
7	4789000.836	4610764.880	4610764.880	%3.72	11	181
8*	4710793.648	4577628.826	4594704.925	%2.83	3	190
9	4788922.375	4589390.606	4580965.205	%4.34	3	190
10	4765705.465	4609656.324	4609463.036	%3.28		
11	4766968.178	4617188.229	4589805.703	%3.72		
12	4748362.991	4660852.307	4586281.591	%3.41		
13	4771435.819	4674991.379	4602062.920	%3.55		
14	4774513.323	4680232.061	4626403.879	%3.10		
15	4771545.621	4669636.665	4640396.475	%2.75		

Overall improvement with respect to p-median solution: %2.83

Computation time in seconds (p-median): 64
Computation time in seconds (random): 1977

p	**Opened DCs (p median)**											**Opened DCs (random)**										
1	6											6										
2	6	38										1	6									
3	6	38	54									1	6	12								
4	3	6	44	54								1	6	12	54							
5	1	6	12	54	64							1	3	12	54	71						
6	1	6	12	28	54	64						1	6	12	28	45	54					
7	1	6	12	28	32	45	54					1	6	12	28	32	45	54				
8*	1	6	21	25	32	45	54	55				1	2	6	25	32	45	54	60			
9	1	21	25	26	28	32	45	54	71			1	2	6	25	32	38	45	54	55		

	Cost composition (min. of p-med&rand)			
p	**shipping**	**fixed**	**safety**	**order+inv**
1	5733083.820	135456.000	10777.059	36543.556
2	5217028.080	207472.000	13698.700	51316.678
3	4894733.700	252743.000	15980.594	61148.195
4	4512969.720	291154.000	19925.922	74272.024
5	4346449.920	277024.000	22290.606	83890.837
6	4112645.070	427280.000	23772.870	91486.751
7	4015791.090	471340.000	25113.521	98520.269
8*	3901208.490	546861.000	25927.399	103631.937
9	3883388.790	559001.000	27418.488	111156.927

Table C.17: Results Obtained by Improvement Type Algorithm for α = 2, β = 2

	p-median					
p	Initial obj. func.	Obj. func. (last)	rand	%impr	time (p)	time (rand)
1	5941774.330	5941774.330	5941774.330		0	0
2	5722161.996	5605151.710	5524470.222	%3.45	9	307
3	5426577.314	5287762.043	5265914.494	%2.96	7	287
4	5135214.515	5072367.478	4949012.069	%3.63	6	258
5	4937507.028	4801281.656	4786694.693	%3.05	5	269
6	4884554.917	4724039.902	4716852.615	%3.43	11	210
7	4854294.530	4671708.649	4676686.832	%3.76	11	174
8	4779705.615	4641017.362	4671205.273	%2.90	3	158
9	4862608.660	4661419.674	4650537.931	%4.36	3	305
10	4842956.932	4669466.357	4669960.041	%3.58	2	152
11*	4847457.229	4697089.936	4639444.262	%4.29	2	137
12	4832039.450	4744491.479	4688035.497	%2.98	2	137
13	4858294.405	4753813.417	4688524.603	%3.49		
14	4863883.698	4761720.858	4726709.304	%2.82		
15	4864678.557	4754918.516	4727165.934	%2.83		

Overall improvement with respect to p-median solution: %2.90

Computation time in seconds (p-median): 61
Computation time in seconds (random): 2394

p	Opened DCs (p median)												Opened DCs (random)											
1	6												6											
2	6	38											1	6										
3	6	38	54										1	6	12									
4	3	6	44	54									1	6	12	54								
5	1	6	12	54	64								1	3	12	54	71							
6	1	6	12	28	54	64							1	6	12	28	45	54						
7	1	6	12	28	32	45	54						1	6	12	28	32	45	54					
8	1	6	21	25	33	42	54	55					1	6	12	28	32	34	45	54				
9	1	21	25	26	28	32	45	54	71				1	6	21	25	32	38	45	54	55			
10	1	6	21	25	26	32	38	45	54	55			1	6	21	25	31	32	38	45	54	55		
11*	1	2	25	26	28	32	38	42	45	54	71		1	2	6	25	32	34	38	45	49	54	55	
12	1	6	21	25	26	28	32	42	45	54	71	80	1	2	6	21	25	32	34	38	40	45	54	55

	Cost composition (for the min. of p-med/random)			
p	shipping	fixed	safety	order+inv
1	5733083,820	135456,000	21554,118	51680,392
2	5217028,080	207472,000	27397,400	72572,742
3	4894733,700	252743,000	31961,187	86476,607
4	4512969,720	291154,000	39851,845	105036,504
5	4346449,920	277024,000	44581,213	118639,560
6	4112645,070	427280,000	47545,740	129381,804
7	4015791,090	471340,000	50227,042	134350,517
8	3901208,490	546861,000	51854,798	141093,074
9	3856277,160	585154,000	53780,343	155326,428
10	3806334,300	645855,000	57162,716	160114,341
11*	3690374,250	712735,000	60185,109	176149,903
12	3656340,600	788112,000	61928,785	181654,112

Table C.18: Results Obtained by Improvement Type Algorithm for $\alpha = 2$, $\beta = 5$

	p-median						
p	**Initial obj. func.**	**Obj. func. (last)**	**rand**	**%impr**	**time (p)**	**time (rand)**	
1	6004138.990	6004138.990	6004138.990		0	0	
2	5807545.772	5687503.159	5607741.160	%3.44	9	309	
3	5532845.460	5392634.113	5364111.188	%3.05	8	283	
4	5260166.714	5196033.876	5069830.627	%3.62	6	243	
5	5072648.884	4935110.778	4922512.567	%2.96	5	229	
6	5029905.797	4868165.044	4863360.016	%3.31	11	240	
7	5009710.790	4825125.515	4832996.713	%3.68	11	226	
8*	4943502.526	4800794.223	4846096.607	%2.89	3	323	
9	5037897.028	4832618.823	4847756.759	%4.07	3	325	
10	5026401.402	4848259.091	4828346.898	%3.94			
11	5038311.038	4886770.747	4852506.573	%3.69			
12	5030139.080	4902425.386	4867490.929	%3.23			
13	5063831.977	4953719.628	4883253.936	%3.57			
14	5075173.945	4968023.608	4918263.544	%3.09			
15	5084693.669	4969918.635	4958001.988	%2.49			

Overall improvement with respect to p-median solution: %2.89

Computation time in seconds (p-median): 56
Computation time in seconds (random): 2178

p	Opened DCs (p median)											Opened DCs (random)										
1	6											6										
2	6	38										1	6									
3	6	38	54									1	6	12								
4	3	6	44	54								1	6	12	54							
5	1	6	12	54	64							1	3	12	54	71						
6	1	6	12	28	54	71						1	6	12	28	45	54					
7	1	6	12	28	32	45	54					1	6	12	28	32	45	54				
8*	1	6	21	25	32	45	54	55				1	6	12	28	32	38	45	54			
9	1	21	25	26	28	32	45	54	71			1	6	21	25	32	34	38	45	55		

	Cost composition (min. of p-med&rand)			
p	**shipping**	**fixed**	**safety**	**order+inv**
1	5733083.820	135456.000	53885.295	81713.875
2	5217028.080	207472.000	68493.500	114747.580
3	4894733.700	252743.000	79902.968	136731.520
4	4512969.720	291154.000	99629.612	166077.295
5	4346449.920	277024.000	111453.032	187585.615
6	4112645.070	427280.000	118864.351	204570.595
7	4015791.090	471340.000	125567.605	212426.819
8*	3901208.490	546861.000	129636.995	223087.738
9	3948770.160	506527.000	139459.457	237862.206

Table C.19: Results Obtained by Improvement Type Algorithm for $\alpha = 2$, $\beta = 10$

	p-median					
p	Initial obj. func.	Obj. func. (last)	rand	%impr	time (p)	time (rand)
1	6091871.280	6091871.280	6091871.280		0	0
2	5926692.269	5802214.717	5723764.663	%3.42	9	580
3	5681604.260	5539273.905	5467031.511	%3.78	7	551
4	5435429.091	5369428.238	5238251.706	%3.63	6	475
5	5261578.603	5122015.024	5111666.106	%2.85	5	397
6	5232731.754	5096773.486	5066960.281	%3.17	4	339
7	5226084.219	5066264.749	5061177.899	%3.16	5	434
8*	5171235.712	5022837.185	5073113.072	%2.87	3	429
9	5281797.977	5085969.464	5057262.501	%4.25	3	444
10	5281219.046	5099605.842	5081066.216	%3.79		
11	5303049.567	5120983.250	5127859.130	%3.43		
12	5304512.279	5190316.391	5139808.330	%3.10		
13	5348379.252	5213419.192	5174060.725	%3.26		
14	5367429.890	5236071.290	5221121.993	%2.73		
15	5388789.611	5249302.146	5252046.582	%2.59		

Overall improvement with respect to p-median solution: %2.87

Computation time in seconds (p-median): 42
Computation time in seconds (random): 3649

p	Opened DCs (p median)											Opened DCs (random)										
1	6											6										
2	6	38										1	6									
3	6	38	54									6	46	54								
4	3	6	44	54								1	6	12	54							
5	1	6	12	54	64							1	3	12	54	71						
6	1	6	21	54	60	64						1	6	12	28	45	54					
7	1	6	21	32	45	54	60					1	6	12	32	45	54	55				
8*	1	6	21	25	32	45	54	55				1	6	12	28	32	38	45	54			
9	1	6	21	25	26	32	45	54	60			1	6	21	25	32	38	45	54	55		

	Cost composition (min. of p-med&rand)			
p	shipping	fixed	safety	order+inv
1	5733083.820	135456.000	107770.590	115560.870
2	5217028.080	207472.000	136987.000	162277.583
3	4832653.800	259418.000	173869.010	201090.701
4	4512969.720	291154.000	199259.224	234868.762
5	4346449.920	277024.000	222906.065	265286.121
6	4112645.070	427280.000	237728.701	289306.510
7	4015720.440	485237.000	248534.504	311685.956
8*	3901208.490	546861.000	259273.989	315493.705
9	3857438.430	585154.000	268740.360	345929.711

Table C.20: Results Obtained by Improvement Type Algorithm for $\alpha = 2$, $\beta = 30$

	p-median					
p	**Initial obj. func.**	**Obj. func. (last)**	**rand**	**%impr**	**time (p)**	**time (rand)**
1	6392008.888	6392008.888	6392008.888		0	0
2	6330705.254	6190427.438	6107413.173	%3.53	9	573
3	6187787.583	6037632.305	5961816.965	%3.65	8	633
4	6032649.934	5877792.215	5808706.022	%3.71	6	727
5*	5903527.609	5769600.178	5751004.004	%2.58	5	703
6	5920492.713	5770333.765	5757909.072	%2.75	3	680
7	5957919.373	5780473.896	5793864.528	%2.98		
8	5940337.534	5783338.993	5829176.980	%2.64		
9	6106218.182	5859238.525	5872780.598	%4.04		
10	6140918.043	5926304.207	5886998.507	%4.13		
11	6194823.741	5951642.643	5941571.215	%4.09		
12	6227173.874	6012244.052	5991432.938	%3.79		
13	6304772.802	6092395.374	6037176.631	%4.24		
14	6348769.752	6112637.896	6095479.048	%3.99		
15	6409024.270	6182135.435	6143090.234	%4.15		

Overall improvement with respect to p-median solution: %2.58

Computation time in seconds (p-median): 31
Computation time in seconds (random): 3316

													Cost composition (min. of p-med&rand)			
p	**Opened DCs (p median)**						**Opened DCs (random)**						**shipping**	**fixed**	**safety**	**order+inv**
1	6						6						5733083.820	135456.000	323311.770	200157.298
2	6	38					6	46					5214417.780	221007.000	397865.982	274122.411
3	6	38	54				1	6	12				4894733.700	252743.000	479417.808	334922.457
4	1	3	54	71			1	6	12	54			4512969.720	291154.000	597777.672	406804.630
5*	1	6	25	54	64		1	3	12	54	71		4348289.520	277024.000	666809.399	458881.086
6	1	6	21	54	60	64	1	6	21	28	45	54	4091759.160	450434.000	716244.858	499471.054

Table C.21: Results Obtained by Improvement Type Algorithm for $\alpha = 2$, $\beta = 50$

	p-median						
p	Initial obj. func.	Obj. func. (last)	rand	%impr	time (p)	time (rand)
1	6665794.730	6665794.730	6665794.730		0	0
2	6697065.780	6541807.951	6452425.261	%3.65	9	676
3	6647872.613	6490230.222	6378889.412	%4.05	7	1005
4*	6569756.785	6405061.977	6325602.358	%3.72	6	847
5	6486450.326	6335403.268	6329075.452	%2.43	5	834
6	6544156.935	6380281.309	6375955.878	%2.57		
7	6620409.549	6426066.354	6428250.894	%2.94		
8	6635854.380	6458168.816	6476749.598	%2.68		
9	6852201.040	6508548.967	6537756.722	%5.02		
10	6916770.242	6565158.541	6599490.455	%5.08		
11	6999861.313	6620630.403	6666444.315	%5.42		
12	7059129.229	6689610.452	6711692.495	%5.23		
13	7166846.853	6758902.559	6765671.143	%5.69		
14	7232735.100	6818356.975	6841865.992	%5.73		
15	7327492.491	6910752.902	6904493.391	%5.77		

Overall improvement with respect to p-median solution: %2.48

Computation time in seconds (p-median): 27
Computation time in seconds (random): 3362

													Cost composition (min. of p-med&rand)			
p	Opened DCs (p median)						Opened DCs (random)						shipping	fixed	safety	order+inv
1	6						6						5733083.820	135456.000	538852.949	258401.961
2	6	38					6	46					5214417.780	221007.000	663109.970	353890.511
3	6	38	54				6	38	54				4894733.700	252743.000	799029.680	432383.033
4*	3	46	54	71			1	6	12	54			4512969.720	291154.000	996296.120	525182.519
5	1	6	25	54	64		1	3	12	54	71		4348289.520	277024.000	1111348.998	592412.934

Table C.22: Results Obtained by Improvement Type Algorithm for $\alpha = 2$, $\beta = 100$

	p-median					
p	Initial obj. func.	Obj. func. (last)	rand	%impr	time (p)	time (rand)
1	7311681.276	7311681.276	7311681.276		0	0
2*	7557845.219	7366333.809	7262121.480	%3.91	9	457
3	7730598.907	7554477.290	7320423.102	%5.31	8	634
4	7778427.655	7604248.367	7385355.079	%5.05		
5	7857344.702	7728404.687	7450913.316	%5.17		
6	8009482.118	7809898.527	7519034.252	%6.12		
7	8175116.377	7851316.853	7593022.624	%7.12		
8	8266920.672	7998867.789	7698688.157	%6.87		
9	8602328.664	8026146.956	7767813.045	%9.70		
10	8735688.125	8108742.541	7836900.241	%10.29		
11	8885475.902	8174776.854	7917378.086	%10.90		
12	9006226.863	8220526.811	8005167.731	%11.12		
13	9182997.858	8306831.827	8091467.503	%11.89		
14	9299141.911	8362203.275	8179800.175	%12.04		
15	9473726.860	8457711.401	8278669.088	%12.61		

Overall improvement with respect to p-median solution: %0.68

Computation time in seconds (p-median): 17
Computation time in seconds (random): 1091

													Cost composition (min. of p-med&rand)			
p	Opened DCs (p median)						Opened DCs (random)						shipping	fixed	safety	order+inv
1	6						6						5733083.820	135456.000	1077705.898	365435.557
2*	6	38					6	46					5214417.780	221007.000	1326219.940	500476.760
3	6	38	54				6	38	76				5199302.610	255439.000	1344370.609	521310.883

Table C.23: Results Obtained by Improvement Type Algorithm for $\alpha = 5$, $\beta = 0.5$

p	Initial obj. func.	Obj. func. (last)	rand	%impr	time (p)	time (rand)
1	14499394.276	14499394.276	14499394.276		0	0
2	13833389.363	13299472.847	13294777.392	%3.89	8	566
3	12986795.859	12552449.220	12360250.565	%4.82	8	523
4	12032378.739	11843387.684	11609264.556	%3.52	6	457
5	11395713.005	11082846.716	11057526.794	%2.97	6	259
6	11099076.929	10785559.602	10744944.453	%3.19	4	296
7	10899726.209	10575805.815	10541592.068	%3.29	3	245
8	10664572.068	10354971.960	10364494.172	%2.81	3	218
9	10672894.850	10165738.284	10172616.188	%4.69	3	264
10	10527151.142	10131767.273	10098259.853	%4.07	3	223
11	10440268.011	10062426.741	10016410.673	%4.06	2	245
12	10252025.819	9994145.514	9961785.540	%2.83	2	227
13	10230186.107	9935336.127	9904093.514	%3.19	2	233
14	10174522.761	9884666.752	9846981.970	%3.22	2	267
15	10078801.087	9803305.036	9848828.930	%2.73	1	235
16	10017490.285	9778621.655	9806249.975	%2.38	1	126
17	9980016.631	9758345.066	9808259.422	%2.22	1	126
18	9972789.324	9740160.933	9787262.239	%2.33	1	127
19	9933004.843	9723096.669	9756681.328	%2.11	1	118
20*	9908232.285	9713641.436	9765495.156	%1.96	1	118
21	9913729.892	9719139.042	9773366.262	%1.96	1	117
22	9971737.987	9745586.491	9751047.297	%2.27		
23	9980041.815	9755238.036	9762165.234	%2.25		
24	10009160.687	9767529.651	9791697.505	%2.41		
25	10014112.913	9764100.161	9771632.024	%2.50		

Overall improvement with respect to p-median solution: %1.96

Computation time in seconds (p-median): 59
Computation time in seconds (random): 4990

p	Opened DCs (p median)																			
1	6																				
2	6	38																			
3	6	41	58																		
4	6	41	44	64																	
5	1	6	12	41	64																
6	1	6	12	41	55	64															
7	1	3	6	12	41	45	55														
8	1	3	6	21	25	41	45	55													
9	1	6	16	21	25	32	34	45	55												
10	1	6	16	21	25	32	34	42	45	55											
11	1	6	16	21	25	32	34	38	42	45	55										
12	1	6	16	21	25	32	34	42	45	46	55	66									
13	1	6	16	19	21	25	28	32	34	40	42	45	46								
14	1	6	16	19	21	25	28	32	34	40	42	45	46	49							
15	1	6	16	19	21	25	28	32	34	40	42	45	46	49	54						
16	1	3	6	16	19	21	25	28	32	34	40	42	45	46	49	54					
17	1	6	10	19	20	21	25	26	28	32	34	40	42	45	46	49	54				
18	1	6	10	20	21	25	26	28	32	34	40	42	45	46	49	54	55	60			
19	1	6	10	20	21	25	26	28	31	32	34	40	42	45	46	49	54	55	60		
20*	1	6	10	20	21	25	26	28	31	32	33	34	40	42	45	46	49	54	55	60	
21	1	2	6	10	50	21	25	26	28	31	32	33	34	40	42	45	46	49	54	55	60

p	Opened DCs (random)																				
1	6																				
2	1	6																			
3	1	6	41																		
4	1	6	12	41																	
5	1	6	12	34	64																
6	1	6	12	34	45	55															
7	1	6	21	25	34	55	64														
8	1	6	21	25	34	45	54	55													
9	1	6	21	25	32	34	45	54	55												
10	1	2	6	21	25	32	34	45	54	55											
11	1	6	16	19	21	25	28	32	34	45	46										
12	1	2	3	6	16	21	25	28	34	38	45	54									
13	1	6	19	21	25	26	28	32	34	38	45	46	54								
14	1	6	16	19	21	25	28	32	34	38	42	45	46	54							
15	1	3	6	16	21	25	34	38	42	45	46	49	54	55	71						
16	1	3	6	16	19	21	25	28	31	32	34	38	42	45	46	54					
17	1	6	16	19	21	25	28	32	34	38	42	45	46	49	54	65	74				
18	1	3	6	16	21	25	28	32	34	38	40	42	45	46	49	54	55	60			
19	1	2	3	6	16	19	21	25	28	31	32	33	34	38	42	45	46	54	65		
20*	1	3	6	10	19	21	25	26	28	31	32	33	34	40	42	45	46	49	54	58	
21	1	3	6	7	16	21	25	28	31	33	34	38	40	42	45	46	49	54	55	60	74

	Cost composition (for the min. of p-med/random)			
p	**shipping**	**fixed**	**safety**	**order+inv**
1	14332709.550	135456.000	5388.529	25840.196
2	13042570.200	207472.000	6849.350	37885.842
3	12005213.250	297269.000	8840.611	48927.704
4	11199477.300	342540.000	9963.558	57283.698
5	10526989.950	453710.000	11222.087	65604.757
6	10141137.525	520335.000	11839.962	71631.966
7	9862910.175	590308.000	12429.356	75944.537
8	9649077.825	620370.000	13226.559	81819.788
9	9406942.875	664430.000	13892.954	87350.359
10	9284848.875	706702.000	14674.335	92034.642
11	9050013.975	853601.000	15252.289	97543.409
12	9010930.425	834283.000	15831.028	100741.087
13	8864703.975	916769.000	16205.916	106414.624
14	8704564.800	1015769.000	16834.233	109813.937
15	8630054.850	1056758.000	17304.511	99187.675
16	8528626.350	1129766.000	17761.994	102467.311
17	8472989.775	1161722.000	18131.017	105502.273
18	8394778.575	1219365.000	18400.199	107617.159
19	8343255.375	1250460.000	19031.765	110349.529
20*	8294372.250	1286638.000	19471.260	113159.926
21	8254023.150	1328910.000	20134.102	116071.791

Table C.24: Results Obtained by Improvement Type Algorithm for α = 5, β = 1

p	Initial obj. func.	Obj. func. (last)	rand	%impr	time (p)	time (rand)
1	14515486.165	14515486.165	14515486.165		0	0
2	13855761.207	13321459.381	13317319.572	%3.89	8	564
3	13014474.591	12580176.341	12389357.695	%4.80	7	528
4	12064958.848	11875494.826	11642955.799	%3.50	6	443
5	11431150.072	11118004.273	11095923.260	%2.93	5	379
6	11137311.833	10823397.089	10786455.347	%3.15	3	293
7	10940773.450	10616484.001	10597689.966	%3.14	3	241
8	10708134.556	10397547.831	10411611.597	%2.77	3	218
9	10719799.716	10211107.779	10222690.845	%4.64	3	265
10	10576055.363	10179362.965	10151056.185	%4.02	4	223
11	10491233.729	10112245.248	10072066.764	%4.00	2	239
12	10304697.999	10046530.103	10014978.161	%2.81	2	231
13	10285042.542	9990087.148	9964377.810	%3.12	2	241
14	10230998.532	9941169.890	9909302.625	%3.14	2	260
15	10137667.534	9861694.427	9913925.660	%2.72	1	234
16	10078093.427	9838826.999	9860433.058	%2.37	1	129
17	10042409.713	9820176.556	9875371.548	%2.21	1	135
18	10036485.096	9803137.619	9862281.021	%2.32	1	129
19	9998417.353	9787836.706	9834461.802	%2.11	1	119
20*	9975401.166	9779985.071	9847119.483	%1.96	1	128
21	9982767.748	9787351.654	9849669.294	%1.96	1	121
22	10042371.472	9815073.343	9827382.277	%2.26		
23	10051998.151	9826060.423	9839811.993	%2.25		
24	10082299.383	9839490.233	9860428.242	%2.41		
25	10088475.450	9837029.256	9857716.516	%2.49		

Overall improvement with respect to p-median solution: %1.96

Computation time in seconds (p-median): 57
Computation time in seconds (random): 5120

p	Opened DCs (p median)																				
1	6																				
2	6	44																			
3	6	41	58																		
4	6	41	44	64																	
5	1	6	12	41	64																
6	1	6	12	41	55	64															
7	1	3	6	12	41	45	55														
8	1	3	6	21	25	41	45	55													
9	1	6	16	21	25	32	34	45	55												
10	1	6	16	21	25	32	34	42	45	55											
11	1	6	16	21	25	32	34	38	42	45	55										
12	1	6	16	21	25	32	34	42	45	46	55	66									
13	1	6	16	19	21	25	28	32	34	40	42	45	46								
14	1	6	16	19	21	25	28	32	34	40	42	45	46	49							
15	1	6	16	19	21	25	28	32	34	40	42	45	46	49	54						
16	1	3	6	16	19	21	25	28	32	34	40	42	45	46	49	54					
17	1	6	10	19	20	21	25	26	28	32	34	40	42	45	46	49	54				
18	1	6	10	20	21	25	26	28	32	34	40	42	45	46	49	54	55	60			
19	1	6	10	20	21	25	26	28	31	32	34	40	42	45	46	49	54	55	60		
20*	1	6	10	20	21	25	26	28	31	32	33	34	40	42	45	46	49	54	55	60	
21	1	2	6	10	20	21	25	26	28	31	32	33	34	40	42	45	46	49	54	55	60

p	Opened DCs (random)																				
1	6																				
2	1	6																			
3	1	6	41																		
4	1	6	12	41																	
5	1	6	12	34	64																
6	1	6	12	34	45	55															
7	1	6	12	32	34	45	55														
8	1	6	21	25	34	45	54	55													
9	1	6	21	25	32	34	45	54	55												
10	1	2	6	21	25	32	34	45	54	55											
11	1	6	16	19	21	25	28	32	34	45	46										
12	1	6	19	21	25	28	32	34	38	45	46	54									
13	1	6	19	21	25	26	28	32	34	38	45	46	54								
14	1	6	16	19	21	25	28	32	34	38	42	45	46	54							
15	1	6	16	21	25	32	34	38	42	45	46	49	54	55	71						
16	1	3	6	16	19	21	25	28	32	34	40	42	45	46	49	54					
17	1	6	16	19	21	25	28	32	34	38	42	45	46	49	54	65	74				
18	1	3	6	16	19	20	21	25	28	34	38	42	45	46	49	54	65	78			
19	1	3	6	16	19	21	25	28	31	32	33	34	38	40	42	45	46	49	54		
20*	1	2	6	10	19	21	25	26	28	31	32	34	40	42	45	46	49	54	58	65	
21	1	3	6	7	10	21	25	26	28	31	33	34	40	42	45	46	49	54	55	60	74

	Cost composition (for the min. of p-med/random)			
p	shipping	fixed	safety	order+inv
1	14332709.550	135456.000	10777.059	36543.556
2	13042570.200	207472.000	13698.700	53578.672
3	12005213.250	297269.000	17681.223	69194.222
4	11199477.300	342540.000	19927.117	81011.382
5	10526989.950	453710.000	22444.173	92779.137
6	10141137.525	520335.000	23679.924	101302.898
7	9899002.575	564395.000	25035.272	109257.119
8	9649077.825	620370.000	26453.118	115710.654
9	9406942.875	664430.000	27785.908	123532.062
10	9284848.875	706702.000	29348.671	130156.639
11	9050013.975	853601.000	30504.578	137947.211
12	8983399.725	856068.000	31361.452	144148.985
13	8864703.975	916769.000	32411.831	150493.004
14	8704564.800	1015769.000	33668.466	155300.360
15	8630054.850	1056758.000	34609.022	140272.555
16	8528626.350	1129766.000	35523.988	144910.661
17	8472989.775	1161722.000	36262.035	149202.746
18	8394778.575	1219365.000	36800.398	152193.646
19	8343255.375	1250460.000	38063.530	156057.800
20*	8294372.250	1286638.000	38942.519	160032.302
21	8254023.150	1328910.000	40268.203	164150.301

Table C.25: Results Obtained by Improvement Type Algorithm for $\alpha = 5$, $\beta = 2$

p	Initial obj. func.	Obj. func.(last)	rand	%impr	time (p)	time (rand)
1	14541400.060	14541400.060	14541400.060		0	0
2	13891546.236	13356765.232	13353211.285	%3.88	8	602
3	13058863.874	12624527.910	12435700.103	%4.77	8	544
4	12117127.190	11927047.736	11696438.930	%3.47	6	449
5	11487891.753	11174252.513	11156797.811	%2.88	5	385
6	11198442.772	10883821.013	10852096.305	%3.09	4	325
7	11006280.350	10681334.261	10657519.728	%3.17	3	246
8	10777544.974	10465396.375	10473059.908	%2.90	3	230
9	10794518.961	10283416.981	10301645.408	%4.73	3	282
10	10653914.174	10255220.958	10213341.558	%4.14	3	236
11	10572292.087	10191524.948	10159710.948	%3.90	2	220
12	10388435.367	10129867.043	10106048.078	%2.72	2	217
13	10372193.037	10077133.780	10051767.936	%3.09	2	252
14	10320660.815	10030941.657	10007298.606	%3.04	1	255
15	10231073.867	9954406.244	9993101.605	%2.70	1	228
16	10174184.777	9934374.948	9976863.801	%2.36	1	120
17	10141289.441	9918240.391	9979547.188	%2.20	1	144
18	10137386.117	9902978.690	9971078.129	%2.31	1	134
19	10102112.191	9890541.494	9947360.109	%2.09	1	124
20*	10081866.897	9885215.141	9949495.343	%1.95	1	135
21	10092264.895	9895613.138	9970571.244	%1.95	1	130
22	10154378.706	9925265.774	9969162.634	%2.26		
23	10166090.221	9938326.698	9961516.333	%2.24		
24	10198223.810	9953537.232	9981176.840	%2.40		
25	10206299.083	9952584.685	10000535.751	%2.49		

Overall improvement with respect to p-median solution: %1.95

Computation time in seconds (p-median): 57
Computation time in seconds (random): 5258

p	Opened DCs (p median)																				
1	6																				
2	6	44																			
3	6	41	58																		
4	6	41	44	64																	
5	1	6	12	41	64																
6	1	6	12	41	55	64															
7	1	3	6	12	41	45	55														
8	1	3	6	21	25	41	45	55													
9	1	6	16	21	25	32	34	45	55												
10	1	6	16	21	25	32	34	42	45	55											
11	1	6	16	21	25	32	34	38	42	45	55										
12	1	6	16	21	25	32	34	42	45	46	55	66									
13	1	6	16	19	21	25	28	32	34	40	42	45	46								
14	1	6	16	19	21	25	28	32	34	40	42	45	46	49							
15	1	6	16	19	21	25	28	32	34	40	42	45	46	49	54						
16	1	3	6	16	19	21	25	28	32	34	40	42	45	46	49	54					
17	1	6	10	19	20	21	25	26	28	32	34	40	42	45	46	49	54				
18	1	6	10	20	21	25	26	28	32	34	40	42	45	46	49	54	55	60			
19	1	6	10	20	21	25	26	28	31	32	34	40	42	45	46	49	54	55	60		
20*	1	6	10	20	21	25	26	28	31	32	33	34	40	42	45	46	49	54	55	60	
21	1	2	6	10	50	21	25	26	28	31	32	33	34	40	42	45	46	49	54	55	60

p	Opened DCs (random)																				
1	6																				
2	1	6																			
3	1	6	41																		
4	1	6	12	41																	
5	1	6	12	34	64																
6	1	6	12	34	45	55															
7	1	6	21	28	32	41	45														
8	1	6	21	28	32	34	45	54													
9	1	6	21	25	32	34	45	54	55												
10	1	3	6	21	25	34	45	46	54	55											
11	1	6	16	19	21	25	28	32	34	45	46										
12	1	6	19	21	25	28	32	34	38	45	46	54									
13	1	3	6	16	21	25	34	38	42	45	46	54	55								
14	1	6	16	19	21	25	28	32	34	38	42	45	46	54							
15	1	6	16	21	25	28	32	34	38	45	46	49	54	55	60						
16	1	3	6	16	19	21	25	28	31	32	34	38	42	45	46	54					
17	1	3	6	16	19	21	25	28	34	38	42	45	46	49	54	65	74				
18	1	3	6	16	19	21	25	28	32	34	38	40	42	45	46	54	58	65			
19	1	3	6	16	19	21	25	28	31	32	33	34	38	40	42	45	46	49	54		
20*	1	3	6	7	10	21	25	26	28	31	33	34	40	42	45	46	49	54	55	60	
21	1	2	6	10	21	25	26	28	31	32	34	38	42	45	46	49	54	55	56	60	65

	Cost composition (for the min. of p-med/random)			
p	**shipping**	**fixed**	**safety**	**order+inv**
1	14332709.550	135456.000	21554.118	51680.392
2	13042570.200	207472.000	27397.400	75771.685
3	12005213.250	297269.000	35362.446	97855.407
4	11199477.300	342540.000	39854.234	114567.396
5	10526989.950	453710.000	44888.347	131209.514
6	10141137.525	520335.000	47359.849	143263.932
7	9907765.200	545880.000	50435.607	153438.920
8	9643427.475	627195.000	52149.860	142624.040
9	9375619.350	700256.000	55631.524	151910.107
10	9190691.925	778929.000	58340.244	185380.389
11	9050013.975	853601.000	61009.156	195086.817
12	8983399.725	856068.000	62722.904	203857.449
13	8799528.675	976923.000	64867.207	210449.054
14	8704564.800	1015769.000	67336.931	219627.875
15	8630054.850	1056758.000	69218.045	198375.350
16	8528626.350	1129766.000	71047.976	204934.622
17	8472989.775	1161722.000	72524.069	211004.547
18	8394778.575	1219365.000	73600.796	215234.319
19	8343255.375	1250460.000	76127.061	220699.058
20*	8294372.250	1286638.000	77885.039	226319.852
21	8254023.150	1328910.000	80536.407	232143.582

Table C.26: Results Obtained by Improvement Type Algorithm for α = 5, β = 5

p	Initial obj. func.	Obj. func. (last)	rand	%impr	time (p)	time (rand)
1	14603764.720	14603764.721	14603764.720		0	0
2	13976930.012	13441426.244	13438341.253	%3.85	8	349
3	13165132.020	12730353.067	12545611.348	%4.71	7	296
4	12242079.389	12050654.160	11822799.843	%3.42	6	241
5	11623456.637	11308497.918	11300381.274	%2.78	5	210
6	11344216.680	11027689.251	11006392.312	%2.98	4	173
7	11162119.638	10835403.438	10837216.771	%2.93	3	146
8	10942330.879	10626505.533	10650555.848	%2.89	3	139
9	10971856.858	10487798.172	10486528.502	%4.42	3	149
10	10838563.694	10467723.193	10429333.322	%3.78	2	126
11	10764275.474	10411414.248	10364597.208	%3.71	2	187
12	10586655.850	10358954.312	10311432.457	%2.60	2	220
13	10578309.793	10314544.884	10318327.714	%2.49	1	184
14	10532530.246	10274617.413	10269474.226	%2.50	1	211
15	10451631.434	10198687.683	10218441.911	%2.42	1	187
16	10400863.894	10160042.378	10220211.640	%2.32	1	115
17	10374392.513	10149649.431	10220252.056	%2.17	1	117
18	10375120.591	10138460.904	10224003.930	%2.28	1	125
19*	10346659.329	10132988.877	10219858.216	%2.07	1	125
20	10332907.326	10133565.953	10212275.217	%1.93	1	123
21	10350666.770	10151325.398	10238027.772	%1.93		
22	10418640.258	10185256.359	10262256.527	%2.24		
23	10435230.739	10203074.099	10272731.405	%2.22		
24	10471555.771	10222411.173	10265006.107	%2.38		
25	10483983.517	10224932.773	10286571.886	%2.47		

Overall improvement with respect to p-median solution: %1.93

Computation time in seconds (p-median): 53
Computation time in seconds (random): 3423

p	Opened DCs (p median)																				
1	6																				
2	6	44																			
3	6	41	58																		
4	6	41	44	64																	
5	1	6	12	41	64																
6	1	6	12	41	55	64															
7	1	3	6	12	41	45	55														
8	1	3	6	21	25	41	45	55													
9	1	6	21	25	26	32	34	45	55												
10	1	6	21	25	26	32	34	42	45	55											
11	1	6	21	25	26	32	34	38	42	45	55										
12	1	6	21	25	26	32	34	42	45	46	55	66									
13	1	6	19	21	25	26	28	32	34	40	42	45	46								
14	1	6	19	21	25	26	28	32	34	40	42	45	46	49							
15	1	6	19	21	25	26	28	32	34	40	42	45	46	49	54						
16	1	3	6	16	19	21	25	28	32	34	40	42	45	46	49	54					
17	1	6	10	19	20	21	25	26	28	32	34	40	42	45	46	49	54				
18	1	6	10	20	21	25	26	28	32	34	40	42	45	46	49	54	55	60			
19*	1	6	10	20	21	25	26	28	31	32	34	40	42	45	46	49	54	55	60		
20	1	6	10	20	21	25	26	28	31	32	33	34	40	42	45	46	49	54	55	60	

p	Opened DCs (random)																				
1	6																				
2	1	6																			
3	1	6	41																		
4	1	6	12	41																	
5	1	6	12	34	64																
6	1	6	12	34	45	55															
7	1	3	6	16	21	28	34														
8	1	6	21	28	32	34	45	54													
9	1	6	21	25	32	34	45	54	55												
10	1	2	6	21	25	32	34	45	54	55											
11	1	6	16	19	21	25	28	32	34	45	46										
12	1	2	3	6	16	21	25	34	38	45	54	55									
13	1	6	16	19	21	25	28	32	34	40	45	49	54								
14	1	3	6	16	21	25	32	34	40	45	46	54	55	60							
15	1	3	6	16	21	25	34	38	42	45	46	49	54	55	60						
16	1	3	6	16	19	21	25	28	31	32	34	38	42	45	46	54					
17	1	6	10	19	21	25	26	28	32	34	38	40	42	45	46	54	65				
18	1	6	16	18	20	21	25	28	32	34	38	42	45	46	49	54	55	60			
19*	1	3	6	7	16	21	25	28	34	38	40	42	45	46	49	54	55	60	65		
20	1	6	16	20	21	25	28	31	32	33	34	38	42	45	46	54	55	60	65	74	

	Cost composition (for the min. of p-med/random)			
p	shipping	fixed	safety	order+inv
1	14332709.550	135456.000	53885.295	81713.875
2	13042570.200	207472.000	68493.500	119805.553
3	12005213.250	297269.000	88406.114	154722.984
4	11199477.300	342540.000	99635.585	181146.958
5	10526989.950	453710.000	112220.866	207460.457
6	10141137.525	520335.000	118399.622	226520.165
7	9929707.350	565571.000	125004.907	215120.181
8	9643427.475	627195.000	130374.650	225508.408
9	9406942.875	664430.000	138929.538	276226.088
10	9284848.875	706702.000	146743.355	291039.093
11	9050013.975	853601.000	152522.891	308459.342
12	8987432.325	848180.000	157115.644	318704.488
13	8887868.700	968646.000	163769.310	294260.874
14	8756229.225	1004703.000	163718.321	344823.680
15	8666351.325	1043222.000	173377.558	315736.800
16	8528626.350	1129766.000	177619.939	324030.089
17	8472989.775	1161722.000	181310.174	333627.483
18	8394778.575	1219365.000	184001.991	340315.339
19*	8343255.375	1250460.000	190317.652	348955.850
20	8294372.250	1286638.000	194712.597	357843.106

Table C.27: Results Obtained by Improvement Type Algorithm for $\alpha = 5$, $\beta = 25$

p	Initial obj. func.	Obj. func. (last)	rand	%impr	time (p)	time (rand)
1	14920309.803	14920309.803	14920309.803		0	0
2	14404386.655	13868676.466	13850890.770	%3.84	9	299
3	13700017.655	13260157.120	13085670.731	%4.48	7	306
4	12873143.804	12674333.906	12445252.136	%3.32	6	261
5	12303580.016	11980862.581	12005699.967	%2.62	5	276
6	12073309.037	11745466.835	11759985.121	%2.72	3	229
7	11938553.919	11601326.232	11593113.724	%2.89	3	176
8	11760575.154	11426747.855	11519736.722	%2.84	3	220
9	11852007.389	11341300.678	11383680.878	%4.31	3	200
10	11753862.617	11321288.011	11366926.565	%3.68	2	189
11	11713853.530	11341818.131	11583171.220	%3.18	2	201
12	11566200.564	11335717.003	11333739.212	%2.01	2	233
13	11595377.585	11306964.689	11331341.526	%2.49	2	185
14	11576446.503	11295662.121	11324187.106	%2.43	2	192
15	11537053.524	11254920.168	11335573.993	%2.45	1	198
16*	11514620.499	11245225.706	11352019.147	%2.34	1	197
17	11518450.163	11261385.483	11394538.500	%2.23	1	202
18	11540811.267	11294704.313	11436755.645	%2.13		
19	11547645.281	11325175.191	11457278.026	%1.93		
20	11565442.368	11354317.300	11494492.376	%1.83		
21	11621097.358	11406211.877	11510352.105	%1.85		
22	11713746.477	11413976.594	11554864.439	%2.56		
23	11753987.824	11454055.469	11598912.080	%2.55		
24	11809831.303	11488850.364	11639418.795	%2.72		
25	11842596.056	11543278.815	11661891.493	%2.53		

Overall improvement with respect to p-median solution: %2.34

Computation time in seconds (p-median): 52
Computation time in seconds (random): 3564

p	Opened DCs (p median)																				
1	6																				
2	6	44																			
3	6	41	58																		
4	6	41	44	64																	
5	1	6	12	41	64																
6	1	6	12	41	55	64															
7	1	3	6	12	41	45	55														
8	1	3	6	21	25	41	45	55													
9	1	6	21	25	26	32	34	45	55												
10	1	6	21	25	26	32	34	42	45	55											
11	1	6	21	25	26	32	34	38	42	45	55										
12	1	6	21	25	26	32	34	42	45	46	55	66									
13	1	6	19	21	25	26	28	32	34	40	42	45	46								
14	1	6	19	21	25	26	28	32	34	40	42	45	46	49							
15	1	6	19	21	25	26	28	32	34	40	42	45	46	49	54						
16*	1	3	6	16	19	21	25	28	32	34	40	42	45	46	49	54					
17	1	6	10	19	20	21	25	26	28	32	34	40	42	45	46	49	54				

p	Opened DCs (random)																				
1	6																				
2	6	46																			
3	6	41	46																		
4	1	6	12	41																	
5	1	6	12	34	64																
6	1	6	12	34	45	55															
7	1	6	21	25	34	45	55														
8	1	3	6	21	28	34	45	54													
9	1	6	21	25	32	34	45	54	55												
10	1	6	21	25	32	34	38	45	54	55											
11	1	6	16	21	25	32	34	38	45	54	55										
12	1	2	3	6	16	21	25	34	38	45	54	55									
13	1	3	6	16	21	25	34	38	42	45	46	54	55								
14	1	3	6	16	21	25	34	38	42	45	46	54	55	65							
15	1	3	6	16	21	25	34	38	42	45	46	54	55	60	65						
16*	1	3	6	7	16	21	25	34	38	42	45	46	49	54	55	60					
17	1	6	16	21	25	28	31	32	34	38	42	45	46	49	54	55	60				

	Cost composition (for the min. of p-med/random)			
p	**shipping**	**fixed**	**safety**	**order+inv**
1	14332709.550	135456.000	269426.475	182717.779
2	13036044.450	221007.000	331554.985	262284.335
3	11998939.500	310804.000	434711.413	341215.818
4	11199477.300	342540.000	498177.923	405056.912
5	10587790.725	425938.000	557195.147	409938.709
6	10209990.825	500912.000	590115.864	444448.146
7	9854857.650	581959.000	618846.822	537450.251
8	9643427.475	627195.000	651873.249	504252.130
9	9422104.650	686720.000	691331.324	541144.704
10	9309776.325	725013.000	715368.330	571130.356
11	9185933.625	810477.000	748933.605	596473.901
12	8989061.700	848180.000	785110.836	711386.677
13	8875210.800	963822.000	813754.361	654177.529
14	8784743.400	999987.000	834540.849	676390.872
15	8651575.725	1038398.000	862329.650	702616.793
16*	8513160.900	1124942.000	885224.535	721898.272
17	8457524.325	1156898.000	903663.478	743299.680

Table C.28: Results Obtained by Improvement Type Algorithm for α = 5, β = 75

p	Initial obj. func.	Obj. func.(last)	rand	%impr	time (p)	time (rand)
1	15592921.450	15592921.450	15592921.450		0	0
2	15303351.988	14959680.377	14706006.200	%3.90	9	292
3	14829495.333	14374383.549	14302919.515	%3.55	7	268
4	14209099.817	13897838.907	13783826.630	%2.99	18	244
5	13736220.950	13441353.558	13486921.535	%2.15	5	273
6	13605523.061	13251057.188	13303719.399	%2.61	4	266
7	13565472.182	13203508.831	13302040.227	%2.67	3	366
8*	13470673.560	13099632.533	13280437.453	%2.75	3	352
9	13690811.501	13118002.540	13224916.133	%4.18	3	329
10	13664265.559	13165873.946	13277111.092	%3.65		
11	13692464.301	13209865.940	13315643.477	%3.52		
12	13605827.742	13264676.151	13385200.847	%2.51		
13	13710717.523	13331936.571	13429267.427	%2.76		
14	13745140.543	13378931.080	13485037.661	%2.66		
15	13789865.690	13413278.759	13543244.733	%2.73		
16	13823337.226	13465739.350	13594299.475	%2.59		
17	13887928.509	13536289.156	13651723.834	%2.53		
18	13953309.669	13592984.290	13731799.114	%2.58		
19	14036266.739	13651067.825	13781784.651	%2.74		
20	14118886.060	13717148.714	13850896.894	%2.85		
21	14255898.165	13769734.460	13925343.078	%3.41		
22	14388534.611	13828459.399	13989655.274	%3.89		
23	14477280.346	13909445.314	14053880.381	%3.92		
24	14571837.041	13977273.367	14149585.438	%4.08		
25	14645056.245	14032232.034	14217212.236	%4.18		

Overall improvement with respect to p-median solution: %2.75

Computation time in seconds (p-median): 52
Computation time in seconds (random): 2390

p	Opened DCs (p median)										Opened DCs (random)									
1	6										6									
2	6	38									6	46								
3	6	41	58								1	6	25							
4	6	41	46	64							1	6	25	41						
5	1	6	25	41	64						1	6	25	34	45					
6	1	6	12	41	55	64					1	6	12	34	45	52				
7	1	3	6	12	41	45	55				1	6	12	32	41	45	55			
8*	1	3	6	21	25	41	45	55			1	3	6	21	25	34	54	55		
9	1	6	21	25	26	32	34	45	55		1	6	21	25	32	34	45	54	55	

	Cost composition (for the min. of p-med/random)			
p	shipping	fixed	safety	order+inv
1	14332709.550	135456.000	808279.424	316476.476
2	13036044.450	221007.000	994664.955	454289.795
3	12327777.000	245942.000	1165824.883	563375.632
4	11290672.050	335739.000	1461386.520	696029.060
5	10678733.475	419137.000	1638087.922	705395.161
6	10209990.825	500912.000	1770347.593	769806.770
7	9929707.350	565571.000	1875073.604	833156.877
8*	9643427.475	627195.000	1955619.748	873390.310
9	9424062.150	686720.000	2071790.621	935429.769

Table C.29: Results Obtained by Improvement Type Algorithm for α = 5, β = 125

p	Initial obj. func.	Obj. func.(last)	rand	%impr	time (p)	time (rand)
1	16223867.297	16223867.297	16223867.297		0	0
2	16142783.558	15464566.428	15501311.978	%4.20	8	279
3	15886085.211	15414787.248	15220383.379	%4.19	7	272
4	15457151.315	15073001.125	14952374.512	%3.27	6	444
5	15074946.254	14738678.249	14831400.269	%2.23	5	437
6*	15035804.374	14614419.272	14744732.104	%2.80	4	489
7	15082159.536	14655922.602	14776988.023	%2.83	3	475
8	15063051.861	14655806.302	14844266.958	%2.70		
9	15402751.943	14696097.025	14895338.767	%4.59		
10	15442095.476	14769576.463	14927447.412	%4.36		
11	15532365.385	14879302.250	15004633.858	%4.20		
12	15501868.100	14983177.841	15086625.288	%3.35		
13	15676121.730	15048145.232	15188173.263	%4.01		
14	15759068.451	15113739.423	15235757.373	%4.09		
15	15881018.436	15221877.777	15334678.894	%4.15		
16	15964377.197	15370549.725	15428832.302	%3.72		
17	16084470.259	15506152.192	15529629.623	%3.60		
18	16188990.009	15590602.035	15601008.858	%3.70		
19	16343819.335	15621131.627	15689799.406	%4.42		
20	16486331.043	15743634.708	15810537.000	%4.50		
21	16700005.051	15859911.120	15913426.280	%5.03		
22	16868029.416	15931714.874	15980254.554	%5.55		
23	17001552.362	16021112.869	16087846.398	%5.77		
24	17131284.518	16114565.881	16174397.317	%5.93		
25	17241313.344	16261283.406	16271327.204	%5.68		

Overall improvement with respect to p-median solution: %2.80

Computation time in seconds (p-median): 33
Computation time in seconds (random): 2396

p	Opened DCs (p median)										Opened DCs (random)									
1	6										6									
2	6	46									6	46								
3	6	41	58								1	6	12							
4	6	41	46	64							1	6	12	34						
5	1	6	25	41	64						1	3	6	12	41					
6*	1	6	21	41	52	64					1	3	6	21	41	52				
7	1	3	6	21	41	45	52				1	6	21	34	45	52	74			

	Cost composition (for the min. of p-med/random)			
p	shipping	fixed	safety	order+inv
1	14332709.550	135456.000	1347132.373	408569.374
2	13036044.450	221007.000	1657774.925	549740.053
3	12236834.250	252743.000	1997574.199	733231.930
4	11177676.900	370312.000	2506723.122	897662.490
5	10678733.475	419137.000	2730146.537	910661.237
6*	10172846.625	535990.000	2914772.113	990810.534
7	9892563.150	600649.000	3089695.052	1073015.399

Table C.30: Results Obtained by Improvement Type Algorithm for $\alpha = 5$, $\beta = 250$

p	Initial obj. func.	Obj. func.(last)	rand	%impr	time (p)	time (rand)
1	17740234.646	17740234.646	17740234.646		0	0
2*	18154207.142	17350051.139	17402017.195	%4.43	8	447
3	18420854.723	17877815.156	17442260.629	%5.31	8	704
4	18291313.360	17889863.537	17540102.520	%4.11		
5	18284270.326	17963058.711	17652437.391	%3.46		
6	18462281.745	17939598.546	17758093.431	%3.81		
7	18712503.737	17984749.236	17863514.828	%4.54		
8	18871659.512	18199265.603	17974598.542	%4.75		
9	19496879.088	18232659.817	18080261.320	%7.27		
10	19692588.012	18364332.721	18224516.438	%7.45		
11	19929051.983	18486096.581	18336167.563	%7.99		
12	20031762.933	18785206.731	18459482.181	%7.85		
13	20370131.603	18908215.721	18589615.459	%8.74		
14	20567316.034	18837876.152	18704310.541	%9.06		
15	20872236.581	18997393.392	18834878.327	%9.76		
16	21071774.063	19094925.349	18953526.951	%10.05		
17	21322921.351	19227911.309	19112906.445	%10.36		
18	21519605.246	19358414.499	19229956.405	%10.64		
19	21847892.190	19460240.982	19362836.059	%11.37		
20	22132917.737	19642660.436	19498912.929	%11.90		
21	22531372.880	19696282.659	19647639.471	%12.80		
22	22781133.673	19804985.111	19798410.151	%13.09		
23	23021143.187	19947637.378	19953604.864	%13.35		
24	23233634.847	20092181.035	20098060.997	%13.52		
25	23430351.829	20223667.626	20242068.584	%13.69		

Overall improvement with respect to p-median solution: %4.43

Computation time in seconds (p-median): 16
Computation time in seconds (random): 1151

p	Opened DCs (p median)											Opened DCs (random)									
1	6											6									
2*	6	46										6	46								
3	6	41	58									6	25	46							

	Cost composition (for the min. of p-med/random)			
p	shipping	fixed	safety	order+inv
1	14332709.550	135456.000	2694264.746	577804.350
2*	13036044.450	221007.000	3315549.851	777449.839
3	12454574.250	259477.000	3736589.270	991620.109

APPENDIX D

THE RESULTS OF THE CONSTRUCTIVE TYPE ALGORITHM FOR THE SENSITIVITY ANALYSIS BASED ON THE TRANSPORTATION AND INVENTORY COST PARAMETERS

Table D.1: Results Obtained by Constructive Type Algorithm for α = 0.5, β = 0.5

p	p-med (initial)	Constructive	DCs opened						shipping	fixed	safety	order+ inv
									Cost composition			
1	1599955.681	1599955.681	6						1433270.955	135456.000	5388.529	25840.196
2	1579313.003	1511825.556	54	71					1382976.030	86729.000	7480.856	34639.670
3	1528410.438	1462504.391	54	71	80				1274577.135	135603.000	8665.805	43658.451
4	1489055.510	1443000.502	3	54	71	80			1173891.270	208611.000	10036.027	50462.205
5*	1494384.177	**1426008.617**	3	12	33	54	71		1117835.550	241186.000	11131.788	55855.279
6	1515500.557	1436544.983	2	3	25	33	54	71				

Overall improvement with respect to p-median solution: %4.23

Computation time in seconds (p-median): 40

Table D.2: Results Obtained by Constructive Type Algorithm for α = 0.5, β = 1

p	p-med (initial)	Constructive	DCs opened						shipping	fixed	safety	order+ inv
									Cost composition			
1	1616047.570	1616047.570	6						1433270.955	135456.000	10777.059	36543.556
2	1601684.847	1533654.632	54	71					1382976.030	86729.000	14961.711	48987.891
3	1555985.544	1489254.119	54	71	80				1274577.135	135603.000	17331.611	61742.373
4	1520823.899	1473938.659	3	54	71	80			1173891.270	208611.000	20072.054	71364.335
5*	1529419.195	**1460276.419**	3	12	33	54	71		1117835.550	241186.000	22263.577	78991.292
6	1553457.379	1473495.965	2	3	25	33	54	71				

Overall improvement with respect to p-median solution: %3.98

Computation time in seconds (p-median): 39

Table D.3: Results Obtained by Constructive Type Algorithm for $\alpha = 0.5$, $\beta = 2$

p	p-med (initial)	Constructive	DCs opened						shipping	fixed	safety	order+ inv
1	1641961.465	1641961.465	6						1433270.955	135456.000	21554.118	51680.392
2	1637469.876	1567594.194	54	71					1381629.240	86729.000	29908.683	69327.271
3	1600228.277	1532160.258	54	71	80				1274577.135	135603.000	34663.222	87316.901
4	1571982.222	1523570.788	3	54	71	80			1173891.270	208611.000	40144.108	100924.410
5*	1585592.291	**1515259.260**	3	12	33	54	71		1117835.550	241186.000	44527.153	111710.557
6	1614195.053	1532775.018	2	3	25	33	54	71				

(Cost composition: shipping, fixed, safety, order+ inv)

Overall improvement with respect to p-median solution: %3.61

Computation time in seconds (p-median): 42

Table D.4: Results Obtained by Constructive Type Algorithm for $\alpha = 0.5$, $\beta = 5$

p	p-med (initial)	Constructive	DCs opened				shipping	fixed	safety	order+ inv
1	1704326.125	1704326.125	6				1433270.955	135456.000	53885.295	81713.875
2	1722853.652	1652745.988	54	71			1381629.240	86729.000	74771.707	109616.040
3*	1706205.649	**1634898.333**	54	71	80		1274577.135	135603.000	86658.055	138060.143
4	1695098.759	1637765.508	25	54	71	80				

(Cost composition: shipping, fixed, safety, order+ inv)

Overall improvement with respect to p-median solution: %3.55

Computation time in seconds (p-median): 23

Table D.5: Results Obtained by Constructive Type Algorithm for $\alpha = 0.5$, $\beta = 7.5$

p	p-med (initial)	Constructive	DCs opened				shipping	fixed	safety	order+ inv
1	1749633.546	1749633.546	6				1433270.955	135456.000	80827.942	100078.649
2	1784486.255	1716826.857	54	71			1383688.890	86729.000	112157.751	134251.216
3*	1782928.536	**1711315.850**	54	71	80		1276636.785	135603.000	129987.405	169088.659
4	1784541.046	1722080.279	25	54	71	80				

(Cost composition: shipping, fixed, safety, order+ inv)

Overall improvement with respect to p-median solution: %2.19

Computation time in seconds (p-median): 23

Table D.6: Results Obtained by Constructive Type Algorithm for $\alpha = 0.5$, $\beta = 12.5$

p	p-med (initial)	Constructive	DCs opened			Cost composition: shipping	fixed	safety	order+ inv
1	1832641.173	1832641.173	6			1433270.955	135456.000	134713.237	129200.980
2*	1896881.963	**1828605.686**	54	71		1381629.240	86729.000	186929.269	173318.178
3	1923140.324	1843346.160	12	54	71				

Overall improvement with respect to p-median solution: %0.22

Computation time in seconds (p-median): 29

Table D.7: Results Obtained by Constructive Type Algorithm for $\alpha = 0.5$, $\beta = 25$

p	p-med (initial)	Constructive	DCs opened		Cost composition: shipping	fixed	safety	order+ inv
1	2020871.208	**2020871.208**	6		1433270.955	135456.000	269426.475	182717.779
2	2150310.295	2068254.888	6	49				

Overall improvement with respect to p-median solution: %0.00

Computation time in seconds (p-median): 5

Table D.8: Results Obtained by Constructive Type Algorithm for $\alpha = 1$, $\beta = 0.5$

p	p-med initial)	Constructive	DCs opened							Cost composition: shipping	fixed	safety	order+ inv
1	3033226.636	3033226.636	6							2866541.910	135456.000	5388.529	25840.196
2	2940877.043	2857007.428	6	80						2629923.750	184330.000	6849.350	35904.328
3	2810413.779	2747201.494	6	54	80					2470281.915	222741.000	8858.284	45320.295
4	2682136.325	2608559.018	1	6	12	54				2256484.860	291154.000	9962.961	50957.197
5	2640308.510	2518500.529	1	3	12	54	71			2173224.960	277024.000	11145.303	57106.266
6*	2640470.257	**2515901.310**	1	2	3	25	54	71		2129830.560	312495.000	11963.485	61612.266
7	2635921.875	2529482.897	1	2	3	25	28	54	71				
8	2604657.665												

Overall improvement with respect to p-median solution: %3.41

Computation time in seconds (p-median): 53

Table D.9: Results Obtained by Constructive Type Algorithm for α = 1, β = 1

p	p-med (initial)	Constructive	DCs opened						shipping	fixed	safety	order+ inv
									Cost composition			
1	3049318.525	3049318.525	6						2866541.910	135456.000	10777.059	36543.556
2	2963248.887	2878728.838	6	80					2629923.750	184330.000	13698.700	50776.388
3	2838092.511	2743029.411	6	54	80				2439041.760	222741.000	17680.081	63566.570
4	2714194.855	2639629.141	1	6	12	54			2256484.860	291154.000	19925.922	72064.359
5*	2675368.875	**2553300.023**	1	3	12	54	71		2173224.960	277024.000	22290.606	80760.456
6	2678427.079	2553440.737	1	2	3	25	54	71				
7	2676800.023											
8	2647764.362											

Overall improvement with respect to p-median solution: %3.57

Computation time in seconds (p-median): 55

Table D.10: Results Obtained by Constructive Type Algorithm for α = 1, β = 2

p	p-med (initial)	Constructive	DCs opened							shipping	fixed	safety	order+ inv
										Cost composition			
1	3075232.420	3075232.420	6							2866541.910	135456.000	21554.118	51680.392
2	2999033.916	2913459.806	6	80						2629923.750	184330.000	27397.400	71808.656
3	2882481.794	2787039.628	6	54	80					2439041.760	222741.000	35360.163	89896.705
4	2765763.501	2694291.763	1	6	12	54				2261350.710	291154.000	39855.699	101931.355
5	2731577.818	2617337.363	1	3	12	54	71			2181208.830	277024.000	44628.621	114475.912
6*	2739164.753	**2613350.856**	1	2	3	25	54	71		2130097.860	312495.000	47783.371	122974.625
7	2742067.789	2628411.662	1	2	3	25	28	54	71				
8	2716530.193												

Overall improvement with respect to p-median solution: %3.80

Computation time in seconds (p-median): 71

Table D.11: Results Obtained by Constructive Type Algorithm for $\alpha = 1, \beta = 5$

p	p-med (initial)	Constructive	DCs opened						Cost composition: shipping	fixed	safety	order+ inv
1	3137597.080	3137597.080	6						2866541.910	135456.000	53885.295	81713.875
2	3084417.692	2996286.705	6	80					2629923.750	184330.000	68493.500	113539.455
3	2988749.940	2892322.338	6	54	80				2439041.760	222741.000	88400.407	142139.171
4	2889694.171	2816538.334	1	6	12	54			2274673.410	284353.000	97415.781	160096.143
5*	2866085.681	**2745910.382**	1	3	12	54	71		2176342.980	277024.000	111562.100	180981.302
6	2883750.744	2756606.153	1	2	3	25	54	71				
7	2897024.988											
8	2880037.153											

Overall improvement with respect to p-median solution: %4.66

Computation time in seconds (p-median): 41

Table D.12: Results Obtained by Constructive Type Algorithm for $\alpha = 1, \beta = 15$

p	p-med (initial)	Constructive	DCs opened						Cost composition: shipping	fixed	safety	order+ inv
1	3305186.378	3305186.378	6						2866541.910	135456.000	161655.885	141532.583
2	3311458.168	3214318.615	6	12					2648514.000	180727.000	200452.951	184624.664
3	3272490.965	3170123.271	1	6	12				2447366.850	252743.000	239708.904	230304.517
4	3222155.021	3125631.758	1	6	12	54			2256484.860	291154.000	298888.836	279104.062
5*	3225042.237	**3097000.939**	1	3	12	54	71		2174144.760	277024.000	333404.699	312427.479
6	3268136.171	3132666.715	1	3	12	25	54	71				

Overall improvement with respect to p-median solution: %3.88

Computation time in seconds (p-median): 64

Table D.13: Results Obtained by Constructive Type Algorithm for $\alpha = 1, \beta = 25$

p	p-med (initial)	Constructive	DCs opened				Cost composition			
							shipping	fixed	safety	order+ inv
1	3454142.163	3454142.163	6				2866541.910	135456.000	269426.475	182717.779
2	3511874.335	3401678.668	6	12			2648514.000	180727.000	334088.252	238349.416
3*	3523635.575	**3396946.542**	1	6	12		2447366.850	252743.000	399514.840	297321.853
4	3512691.337	3403711.639	1	6	25	54				

Overall improvement with respect to p-median solution: %3.30

Computation time in seconds (p-median): 36

Table D.14: Results Obtained by Constructive Type Algorithm for $\alpha = 1, \beta = 50$

p	p-med (initial)	Constructive	DCs opened		Cost composition			
					shipping	fixed	safety	order+ inv
1*	3799252.820	**3799252.820**	6		2866541.910	135456.000	538852.949	258401.961
2	3973937.700	3834321.715	6	12				

Overall improvement with respect to p-median solution: %0.00

Computation time in seconds (p-median): 5

Table D.15: Results Obtained by Constructive Type Algorithm for $\alpha = 2, \beta = 0.5$

p	p-med (initial)	Constructive	DCs opened												Cost composition			
															shipping	fixed	safety	order+ inv
1	5899768.546	5899768.546	6												5733083.820	135456.000	5388.529	25840.196
2	5664005.123	5467635.801	1	6											5217028.080	207472.000	6849.350	36286.371
3	5354509.299	5178288.493	1	6	54										4877583.360	245883.000	8682.400	46139.733
4	5050708.437	4868630.832	1	6	12	54									4514889.330	291154.000	9971.340	52616.162
5	4845692.245	4724948.482	1	6	25	45	54								4294764.360	359402.000	11127.082	59655.039
6	4785553.039	4616502.407	1	6	12	28	45	54							4112645.070	427280.000	11886.435	64690.902
7	4748104.353	4585656.146	1	6	21	25	28	45	54						4016335.590	488904.000	12402.989	68013.567
8	4667583.618	4553356.975	1	2	6	25	32	45	54	55					3945269.040	520708.000	13199.591	74180.345
9	4742747.922	4539060.372	1	2	6	25	32	45	49	54	55				3890685.840	556873.000	13612.070	77889.462
10	4717230.701	4531968.829	1	2	6	25	32	38	45	49	54	55			3840474.030	595166.000	14098.916	82229.883
11*	4716405.020	**4517867.626**	1	2	6	25	32	34	38	45	49	54	55		3702042.690	712735.000	15028.171	88061.765
12	4695733.881	4525397.572	1	2	6	10	25	32	34	38	45	49	54	55				

Overall improvement with respect to p-median solution: %3.21

Computation time in seconds (p-median): 120

Table D.16: Results Obtained by Constructive Type Algorithm for $\alpha = 2, \beta = 1$

p	p-med (initial)	Constructive	DCs opened												shipping	fixed	safety	order+ inv
															Cost composition			
1	5915860.435	5915860.435	6												5733083.820	135456.000	10777.059	36543.556
2	5686376.967	5489515.458	1	6											5217028.080	207472.000	13698.700	51316.678
3	5382188.031	5163457.882	1	6	54										4835264.100	245883.000	17680.081	64630.700
4	5083131.021	4900396.499	1	6	12	54									4514889.330	291154.000	19942.680	74410.490
5	4880978.553	4760785.490	1	6	25	45	54								4294764.360	359402.000	22254.165	84364.966
6	4823637.183	4655184.691	1	6	12	28	45	54							4112645.070	427280.000	23772.870	91486.751
7	4789000.836	4626231.278	1	6	21	25	28	45	54						4016335.590	488904.000	24805.979	96185.709
8	4710793.648	4597283.070	1	2	6	25	32	45	54	55					3945269.040	520708.000	26399.181	104906.849
9	4788922.375	4592623.524	1	2	6	25	32	38	45	54	55				3895057.230	559001.000	27384.640	111180.654
10	4765705.465	4580128.479	1	2	6	25	32	38	45	49	54	55			3840474.030	595166.000	28197.833	116290.616
11*	4766968.178	**4569372.174**	1	2	6	25	32	34	38	45	49	54	55		3702042.690	712735.000	30056.341	124538.142
12	4748362.991	4578547.805	1	2	6	10	25	32	34	38	45	49	54	55				

Overall improvement with respect to p-median solution: %3.0

Computation time in seconds (p-median): 110

Table D.17: Results Obtained by Constructive Type Algorithm for $\alpha = 2, \beta = 2$

p	p-med (initial)	Constructive	DCs opened									
1	5941774.330	5941774.330	6									
2	5722161.996	5524470.222	1	6								
3	5426577.314	5207908.876	1	6	54							
4	5135214.515	4951161.013	1	6	12	54						
5	4937507.028	4817984.768	1	6	25	45	54					
6	4884554.917	4716852.615	1	6	12	28	45	54				
7	4854294.530	4690878.681	1	6	21	25	28	45	54			
8	4779705.615	4688920.749	1	2	6	25	32	45	54	60		
9*	4862608.660	**4669037.714**	1	2	6	25	32	45	49	54	60	
10	4842956.932	4681950.363	1	2	6	25	32	38	45	49	54	60

Cost composition			
shipping	fixed	safety	order+ inv
5733083.820	135456.000	21554.118	51680.392
5217028.080	207472.000	27397.400	72572.742
4835264.100	245883.000	35360.163	91401.613
4514889.330	291154.000	39885.359	105232.324
4294764.360	359402.000	44508.329	119310.079
4112645.070	427280.000	47545.740	129381.804
4016335.590	488904.000	49611.957	136027.134
3977063.580	510094.000	52721.851	149041.318
3912175.170	546259.000	54352.032	156251.512

Overall improvement with respect to p-median solution: %2.32

Computation time in seconds (p-median): 85

Table D.18: Results Obtained by Constructive Type Algorithm for $\alpha = 2, \beta = 5$

p	p-med (initial)	Constructive	DCs opened								
1	6004138.990	6004138.990	6								
2	5807545.772	5607741.160	1	6							
3	5532845.460	5364677.644	1	6	12						
4	5260166.714	5069830.627	1	6	12	54					
5	5072648.884	4926114.192	1	3	12	54	71				
6	5029905.797	4883433.981	1	3	12	28	54	71			
7	5009710.790	4850670.442	1	3	6	21	25	54	55		
8*	4943502.526	**4828769.139**	1	3	6	21	25	45	54	55	
9	5037897.028	4840580.207	1	3	6	21	25	38	45	54	55

Cost composition			
shipping	fixed	safety	order+ inv
5733083.820	135456.000	53885.295	81713.875
5217028.080	207472.000	68493.500	114747.580
4895447.070	252743.000	79890.321	136597.253
4512969.720	291154.000	99629.612	166077.295
4349912.670	277024.000	111462.634	187714.887
4222732.020	338101.000	119268.320	203332.640
4010051.970	500760.000	123126.593	216731.879
3889170.090	575809.000	130361.621	233428.428

Overall improvement with respect to p-median solution: %2.32

Computation time in seconds (p-median): 99

Table D.19: Results Obtained by Constructive Type Algorithm for $\alpha = 2, \beta = 10$

p	p-med (initial)	Constructive	DCs opened	Cost composition: shipping	fixed	safety	order+ inv
1	6091871.280	6091871.280	6	5733083.820	135456.000	107770.590	115560.870
2	5926692.269	5723764.663	1 6	5217028.080	207472.000	136987.000	162277.583
3	5681604.260	5500650.207	1 6 12	4894733.700	252743.000	159805.936	193367.571
4	5435429.091	5244639.961	1 6 12 54	4518935.160	291154.000	199320.133	235230.668
5	5261578.603	5115330.878	1 3 12 54 71	4349912.670	277024.000	222925.269	265468.939
6	5232731.754	5082236.237	1 3 12 28 54 71	4217711.340	338101.000	238594.177	287829.720
7	5226084.219	5074564.585	1 3 12 28 45 54 71	4096661.340	413150.000	252856.063	311897.182
8*	5171235.712	**5047759.716**	1 6 21 25 32 45 54 55	3915058.140	546861.000	258770.666	327069.910
9	5281797.977	5067093.327	1 2 6 21 25 32 45 54 55				

Overall improvement with respect to p-median solution: %2.39

Computation time in seconds (p-median): 107

Table D.20: Results Obtained by Constructive Type Algorithm for $\alpha = 2, \beta = 30$

p	p-med (initial)	Constructive	DCs opened	Cost composition: shipping	fixed	safety	order+ inv
1	6392008.888	6392008.888	6	5733083.820	135456.000	323311.770	200157.298
2	6330705.254	6107413.173	6 46	5214417.780	221007.000	397865.982	274122.411
3	6187787.583	5961816.965	1 6 12	4894733.700	252743.000	479417.808	334922.457
4	6032649.934	5808706.022	1 6 12 54	4512969.720	291154.000	597777.672	406804.630
5	5903527.609	5755518.167	1 3 12 54 71	4349912.670	277024.000	668775.806	459805.691
6*	5920492.713	**5754008.830**	1 3 21 25 54 71	4231876.680	338648.000	697481.232	486002.917
7	5957919.373	5788352.231	1 3 21 25 54 55 71				

Overall improvement with respect to p-median solution: %2.53

Computation time in seconds (p-median): 88

Table D.21: Results Obtained by Constructive Type Algorithm for $\alpha = 2, \beta = 50$

p	p-med (initial)	Constructive	DCs opened					Cost composition shipping	fixed	safety	order+ inv
1	6665794.730	6665794.730	6					5733083.820	135456.000	323311.770	200157.298
2	6697065.780	6452425.261	6	46				5214417.780	221007.000	397865.982	274122.411
3	6647872.613	6378889.412	1	6	12			4894733.700	252743.000	479417.808	334922.457
4*	6569756.785	**6325602.358**	1	6	12	54		4512969.720	291154.000	597777.672	406804.630
5	6486450.326	6329075.452	1	3	12	54	71	4349912.670	277024.000	668775.806	459805.691

Overall improvement with respect to p-median solution: %2.48

Computation time in seconds (p-median): 45

Table D.22: Results Obtained by Constructive Type Algorithm for $\alpha = 2, \beta = 100$

p	p-med (initial)	Constructive	DCs opened			Cost composition shipping	fixed	safety	order+ inv
1	7311681.276	7311681.276	6			5733083.820	135456.000	1077705.898	365435.557
2*	7557845.219	**7262121.480**	6	46		5214417.780	221007.000	1326219.940	500476.760
3	7730598.907	7320423.102	6	46	76				

Overall improvement with respect to p-median solution: %0.68

Computation time in seconds (p-median): 13

Table D.23: Results Obtained by Constructive Type Algorithm for $\alpha = 5, \beta = 0.5$

																					Cost composition			
p	p-med (initial)	Constructive	DCs opened																		shipping	fixed	safety	order+ inv
1	14499394.276	14499394.276	6																		14332709.550	135456.000	5388.529	25840.196
2	13833389.363	13294777.392	1	6																	13042570.200	207472.000	6849.350	37885.842
3	12986795.859	12363472.206	1	6	34																11980744.575	325041.000	8890.451	48796.180
4	12032378.739	11609264.556	1	6	12	41															11199477.300	342540.000	9963.558	57283.698
5	11395713.005	11041015.632	1	6	12	34	45														10518937.425	445361.000	11162.507	65554.700
6	11099076.929	10783300.038	1	6	12	28	41	64													10213044.375	487015.000	11934.084	71306.580
7	10899726.209	10665522.889	1	6	21	32	41	45	60												10027814.850	549163.000	12304.088	76240.950
8	10664572.068	10394082.291	1	3	6	21	25	41	45	55											9672254.475	627195.000	13030.556	81602.260
9	10672894.850	10194746.549	1	3	6	21	25	34	45	54	55										9399929.700	693378.000	13948.911	87489.939
10	10527151.142	10120390.214	1	2	3	6	21	25	34	45	54	55									9277835.700	735650.000	14730.292	92174.222
11	10440268.011	10036939.699	1	3	6	21	25	34	38	45	46	54	55								9107300.775	817222.000	15060.740	97356.184
12	10252025.819	9955946.905	1	3	6	16	21	25	34	38	45	46	54	55							8947669.200	891459.000	15533.433	101285.272
13	10230186.107	9913683.875	1	3	6	16	21	25	34	38	45	46	49	54	55						8864563.500	927624.000	15970.023	105526.353
14	10174522.761	9883809.945	1	3	6	16	21	25	34	40	45	46	49	54	55	60					8761000.050	996808.000	16393.018	109608.878
15	10078801.087	9845386.804	1	3	6	16	21	25	34	40	42	45	46	49	54	55	60				8632752.975	1082272.000	17047.284	113314.545
16	10017490.285	9819077.999	1	3	6	16	21	25	28	34	40	42	45	46	49	54	55	60			8541249.000	1143349.000	17624.611	116855.387
17*	9980016.631	**9802642.943**	1	3	6	16	21	25	28	31	34	40	42	45	46	49	54	55	60		8489725.800	1174444.000	18256.178	120216.966
18	9972789.324	9809003.923	1	2	3	6	16	21	25	28	31	34	40	42	45	46	49	54	55	60				
19	9933004.843																							
20	9908232.285																							

Overall improvement with respect to p-median solution: %0.63

Computation time in seconds (p-median): 208

Table D.24: Results Obtained by Constructive Type Algorithm for α = 5, β = 1

p	p-med (initial)	Constructive	DCs opened																		Cost composition			
																					shipping	fixed	safety	order+ inv
1	14515486.165	14515486.165	6																		14332709.550	135456.000	10777.059	36543.556
2	13855761.207	13317319.572	1	6																	13042570.200	207472.000	13698.700	53578.672
3	13014474.591	12392574.697	1	6	34																11980744.575	325041.000	17780.902	69008.220
4	12064958.848	11642955.799	1	6	12	41															11199477.300	342540.000	19927.117	81011.382
5	11431150.072	11079331.785	1	6	12	34	45														10518937.425	445361.000	22325.015	92708.346
6	11137311.833	10824770.274	1	6	12	28	41	64													10213044.375	487015.000	23868.167	100842.732
7	10940773.450	10647780.646	1	6	21	25	41	55	64												9954150.375	562536.000	24634.291	106459.980
8	10708134.556	10453709.911	1	6	21	25	34	54	55	64											9683262.675	628719.000	26523.602	115204.634
9	10719799.716	10356796.262	1	3	6	21	25	34	45	54	55										9511020.150	693378.000	28273.569	124124.543
10	10576055.363	10181364.454	1	2	3	6	21	25	34	45	54	55									9285983.700	735650.000	29486.180	130244.574
11	10491233.729	10104956.302	1	3	6	21	25	34	38	45	46	54	55								9120019.650	817222.000	30149.716	137564.937
12	10304697.999	10057796.102	1	3	6	21	25	34	38	42	45	46	54	55							8980653.225	902686.000	31452.306	143004.571
13	10285042.542	9983805.105	1	3	6	16	21	25	34	38	42	45	46	54	55						8826057.825	976923.000	32413.230	148411.050
14	10230998.532	9939486.550	1	3	6	16	21	25	34	38	42	45	46	49	54	55					8738662.875	1013088.000	33288.151	154447.523
15	10137667.534	9913610.102	1	3	6	16	21	25	34	38	42	45	46	49	54	55	60				8642789.475	1077448.000	33973.625	159399.002
16	10078093.427	9889338.636	1	3	6	16	21	25	28	34	38	42	45	46	49	54	55	60			8551285.500	1138525.000	35128.236	164399.901
17*	10042409.713	**9874927.558**	1	3	6	16	21	25	28	31	34	38	42	45	46	49	54	55	60		8499762.300	1169620.000	36391.368	169153.891
18	10036485.096	9883515.135	1	2	3	6	16	21	25	28	31	34	38	42	45	46	49	54	55	60				
19	9998417.353																							
20	9975401.166																							

Overall improvement with respect to p-median solution: %1.30

Computation time in seconds (p-median): 205

Table D.25: Results Obtained by Constructive Type Algorithm for α = 5, β = 2

p	p-med (initial)	Constructive	DCs opened	Cost composition: shipping	Cost composition: fixed	Cost composition: safety	Cost composition: order+ inv
1	14541400.060	14541400.060	6	14332709.550	135456.000	21554.118	51680.392
2	13891546.236	13353211.285	1 6	13042570.200	207472.000	27397.400	75771.685
3	13058863.874	12438939.739	1 6 34	11980744.575	325041.000	35561.804	97592.360
4	12117127.190	11696438.930	1 6 12 41	11199477.300	342540.000	39854.234	114567.396
5	11487891.753	11195716.616	1 6 12 41 45	10603537.350	417589.000	44240.738	130349.528
6	11198442.772	10915424.885	1 6 21 28 41 64	10215236.475	510169.000	47945.482	142073.928
7	11006280.350	10692297.317	1 6 21 28 34 54 64	9910195.650	576352.000	51640.721	154108.946
8	10777544.974	10513553.912	1 6 21 28 32 34 45 54	9681574.425	612063.000	54157.753	165758.735
9	10794518.961	10365451.501	1 6 21 25 28 32 34 45 54	9484442.400	650533.000	56028.272	174447.829
10	10653914.174	10262399.297	1 2 3 6 21 25 34 45 54 55	9283524.900	735650.000	58972.963	184251.434
11	10572292.087	10189686.874	1 3 6 21 25 34 38 45 46 54 55	9117560.850	817222.000	60300.034	194603.990
12	10388435.367	10125872.541	1 3 6 16 21 25 34 38 45 46 54 55	8969844.150	891459.000	62121.539	202447.852
13	10372193.037	10087688.286	1 3 6 16 21 25 34 38 45 46 49 54 55	8885464.650	927624.000	63824.684	210774.952
14	10320660.815	10076509.508	1 3 6 16 21 25 31 34 38 45 46 49 54 55	8833941.450	958719.000	66350.949	217498.109
15	10231073.867	10054951.352	1 3 6 16 21 25 31 34 38 45 46 49 54 55 60	8739341.850	1023079.000	67780.325	224750.177
16	10174184.777	10015777.432	1 3 6 16 21 25 31 34 38 42 45 46 49 54 55 60	8604614.775	1108543.000	70407.450	232212.207
17	10141289.441	9997974.979	1 3 6 16 21 25 31 32 34 38 42 45 46 49 54 55 60	8533984.275	1152603.000	71919.728	239467.976
18	10137386.117	9982301.941	1 3 6 16 21 25 28 31 32 34 38 42 45 46 49 54 55 60	8448114.300	1213680.000	73946.121	246561.520
19	10102112.191	9964786.489	1 3 6 16 19 20 21 25 28 31 32 34 38 42 45 46 49 54 60	8332617.600	1301386.000	75994.580	254788.309
20*	10081866.897	**9960389.793**	1 3 6 16 19 20 21 25 28 31 32 33 34 38 42 45 46 49 54 60	8283734.475	1337564.000	77752.558	261338.760
21		9972219.724	1 2 6 16 19 20 21 25 26 28 31 32 33 34 38 42 45 46 49 54 60				

Overall improvement with respect to p-median solution: %1.20

Computation time in seconds (p-median): 247

Table D.26: Results Obtained by Constructive Type Algorithm for $\alpha = 5$, $\beta = 5$

p	p-med (initial)	Constructive	DCs opened																				Cost composition			
																							shipping	fixed	safety	order+ inv
1	14603764.720	14603764.720	6																				14332709.550	135456.000	53885.295	81713.875
2	13976930.012	13438341.253	1	6																			13042570.200	207472.000	68493.500	119805.553
3	13165132.020	12548997.155	1	6	34																		11980744.575	325041.000	88904.509	154307.070
4	12242079.389	11822799.843	1	6	12	41																	11199477.300	342540.000	99635.585	181146.958
5	11623456.637	11337828.894	1	6	12	41	45																10603537.350	417589.000	110601.844	206100.701
6	11344216.680	11069907.785	1	6	21	28	41	64															10215236.475	510169.000	119863.705	224638.605
7	11162119.638	10858787.976	1	6	21	28	32	41	45														9943693.950	545880.000	126013.801	243200.225
8	10942330.879	10680448.225	1	6	21	28	32	34	45	54													9671369.175	612063.000	135197.350	261818.699
9	10971856.858	10558695.621	1	6	21	25	32	34	45	54	55												9478351.425	664430.000	138974.763	276939.433
10	10838563.694	10420958.651	1	6	21	25	32	34	45	46	54	55											9233647.500	749981.000	144940.456	292389.694
11	10764275.474	10366655.228	1	6	21	25	32	34	38	45	46	54	55										9121319.175	788274.000	149753.499	307308.554
12	10586655.850	10303410.462	1	3	6	16	21	25	34	38	45	46	54	55									8936784.825	891459.000	155279.510	319887.127
13	10578309.793	10272678.678	1	3	6	16	21	25	34	38	45	46	49	54	55								8852405.325	927624.000	159541.531	333107.822
14	10532530.246	10263515.796	1	3	6	16	21	25	34	40	45	46	49	54	55	60							8756595.675	996808.000	163869.741	346242.380
15	10451631.434	10243829.870	1	3	6	16	21	25	34	40	42	45	46	49	54	55	60						8632752.975	1082272.000	170472.840	358332.056
16	10400863.894	10230436.738	1	3	6	16	20	21	25	34	40	42	45	46	49	54	55	60					8579760.075	1163261.000	175040.095	371637.867
17	10374392.513	10215825.931	1	3	6	16	20	21	25	32	34	40	42	45	46	49	54	55	60				8506929.000	1207321.000	178381.390	382450.961
18	10375120.591	10202243.875	1	6	16	20	21	25	26	28	32	34	40	42	45	46	49	54	55	60			8368226.100	1256091.000	183809.580	394117.195
19*	10346659.329	**10198761.581**	1	6	16	20	21	25	26	28	31	32	34	40	42	45	46	49	54	55	60		8316702.900	1287186.000	190125.242	404747.440
20	10332907.326	10219251.252	1	2	6	16	20	21	25	26	28	31	32	34	40	42	45	46	49	54	55	60				

Overall improvement with respect to p-median solution: %1.30

Computation time in seconds (p-median): 277

Table D.27: Results Obtained by Constructive Type Algorithm for $\alpha = 5$, $\beta = 25$

p	p-med (initial)	Constructive	DCs opened												Cost composition: shipping	fixed	safety	order+ inv
1	14920309.803	14920309.803	6												14332709.550	135456.000	269426.475	182717.779
2	14404386.655	13853091.474	6	46											13038460.050	221007.000	331538.296	262086.128
3	13700017.655	13090208.306	6	41	46										12002924.850	310804.000	434672.526	341806.930
4	12873143.804	12455886.454	1	6	12	41									11208513.675	342540.000	498566.991	406265.788
5	12303580.016	12091983.813	1	6	24	41	45								10636680.900	438162.000	557376.609	459764.304
6	12073309.037	11830291.211	1	6	21	41	60	64							10228853.025	513452.000	586877.953	501108.233
7	11938553.919	11656066.664	1	3	6	21	25	41	55						9956089.650	552146.000	615650.862	532180.153
8	11760575.154	11521224.979	1	3	6	21	25	41	45	55					9664576.950	627195.000	652317.788	577135.241
9	11852007.389	11397595.329	1	3	6	21	25	34	45	54	55				9386516.250	693378.000	698411.466	619289.613
10	11753862.617	11369048.322	1	3	6	16	21	25	34	45	54	55			9231920.850	767615.000	722611.940	646900.533
11*	11713853.530	**11351731.994**	1	3	6	16	21	25	34	38	45	54	55		9121221.900	805908.000	746101.567	678500.527
12	11566200.564	11364467.437	1	3	6	16	21	25	34	38	42	45	54	55				

Overall improvement with respect to p-median solution: %1.41

Computation time in seconds (p-median): 150

Table D.28: Results Obtained by Constructive Type Algorithm for $\alpha = 5$, $\beta = 75$

p	p-med (initial)	Constructive	DCs opened								Cost composition: shipping	fixed	safety	order+ inv
1	15592921.450	15592921.450	6								14332709.550	135456.000	808279.424	316476.476
2	15303351.988	14706006.200	6	46							13036044.450	221007.000	994664.955	454289.795
3	14829495.333	14204880.873	6	41	46						11998939.500	310804.000	1304134.240	591003.133
4	14209099.817	13738034.315	1	6	12	41					11199729.300	342540.000	1494592.784	701172.231
5	13736220.950	13516855.271	1	6	12	41	45				10642670.700	417589.000	1659608.065	796987.506
6	13605523.061	13366626.438	1	6	21	41	60	64			10224615.675	513452.000	1760817.785	867740.978
7*	13565472.182	**13262365.705**	1	6	21	25	41	55	64		9923710.950	562536.000	1850893.737	925225.019
8	13470673.560	13276475.403	1	3	6	21	25	41	45	55				

Overall improvement with respect to p-median solution: %1.55

Computation time in seconds (p-median): 115

Table D.29: Results Obtained by Constructive Type Algorithm for $\alpha = 5, \beta = 125$

p	p-med (initial)	Constructive	DCs opened							Cost composition: shipping	fixed	safety	order+ inv
1	16223867.297	16223867.297	6							14332709.550	135456.000	1347132.373	408569.374
2	16142783.558	15501311.978	6	46						13036044.450	221007.000	1657774.925	586485.603
3	15886085.211	15282803.825	6	25	46					12446783.625	259477.000	1871998.452	704544.748
4	15457151.315	14964937.405	1	6	25	41				11301711.150	335739.000	2430943.766	896543.490
5	15074946.254	14848999.853	1	3	6	12	41			10618633.575	415548.000	2782704.515	1032113.763
6*	15035804.374	**14748882.259**	1	3	6	21	41	52		10195555.950	525600.000	2908513.718	1119212.591
7	15082159.536	14767823.649	1	6	21	25	41	45	55				

Overall improvement with respect to p-median solution: %1.91

Computation time in seconds (p-median): 65

Table D.30: Results Obtained by Constructive Type Algorithm for $\alpha = 5, \beta = 250$

p	p-med (initial)	Constructive	DCs opened			Cost composition: shipping	fixed	safety	order+ inv
1	17740234.646	17740234.646	6			14332709.550	135456.000	2694264.746	577804.350
2*	18154207.142	**17402017.195**	6	46		13036044.450	221007.000	3315549.851	829415.894
3	18420854.723	17442260.629	6	25	46				

Overall improvement with respect to p-median solution: %4.14

Computation time in seconds (p-median): 17

APPENDIX E

THE RESULTS OF THE SENSITIVITY ANALYSIS FOR REDUCED ORDERING COST

Table E.1: Results Obtained for the Problem with Reduced Order Cost ($\alpha = 1, \beta = 1$)

	p-median			
p	**Initial obj. func.**	**Obj. func. (last)**	**Rand**	**Constructive**
1	3019417.879	3019417.879	3019417.879	3019417.879
2	2923298.358	2864983.720	2840580.289	2840580.289
3	2790625.389	2720971.159	2696532.218	2728196.212
4	2662341.996	2616364.349	2588469.038	2588469.038
5	2619637.433	2496989.407	2496989.407	2498757.284
6*	2617835.578	2497031.018	2497031.018	2493406.468
7	2611736.805	2509109.166	2505459.570	2500675.854
8	2579287.888	2525405.489	2528059.462	

Overall improvement with respect to p-median solution: %4.59

Computation time in seconds (p-median): 23
Computation time in seconds (random): 1683
Computation time in seconds (constructive): 38

p	**Opened DC (p median)**								**Opened DC(random)**								**Opened DC(constructive)**							
1	6								6								6							
2	6	38							6	80							6	80						
3	6	38	54						6	54	80						6	54	80					
4	2	3	54	71					1	6	12	54					1	6	12	54				
5	1	3	12	54	71				1	3	12	54	71				1	3	12	54	71			
6*	1	3	12	28	54	71			1	3	12	28	54	71			1	2	3	25	54	71		
7	1	12	28	32	45	54	71		1	10	12	28	32	54	71		1	2	3	25	28	54	71	
8	1	2	25	32	45	54	71	60	1	10	12	28	32	54	71	74								

Cost composition (for the best objective function)			
shipping	**fixed**	**safety**	**order+ inv**
2129830.560	312495.000	23926.970	27153.938

Table E.2: Results Obtained for the Problem with Reduced Order Cost ($\alpha = 1, \beta = 15$)

	p-median			
p	Initial obj. func.	Obj. func. (last)	Rand	Constructive
1	3189381.675	3189381.675	3189381.675	3189381.675
2	3156730.435	3087329.351	3068641.660	3068641.660
3	3088651.595	3012618.896	2993093.393	2993093.393
4	3021329.759	2935715.940	2927489.531	2931157.517
5*	3008474.440	2883816.239	2879187.973	2880749.444
6	3035273.385	2923256.517	2912616.598	2901251.192
7	3057364.336	2957943.703	2947195.264	

Overall improvement with respect to p-median solution: %4.25

Computation time in seconds (p-median): 15
Computation time in seconds (random): 1375
Computation time in seconds (constructive): 24

p	Opened DC (p median)							Opened DC (random)							Opened DC (constructive)						
1	6							6							6						
2	6	38						6	80						6	80					
3	6	38	54					6	54	80					6	54	80				
4	1	3	54	71				1	6	12	54				1	6	25	54			
5*	1	3	25	54	71			1	3	12	54	71			1	3	12	54	71		
6	1	3	12	54	60	71		1	3	12	54	71	74		1	3	12	25	54	71	
7	1	10	12	32	54	60	71	1	10	12	32	54	71	74							

Cost composition (for the best objective function)			
shipping	fixed	safety	order+ inv
2174144.760	277024.000	333404.699	94614.513

Table E .3: Results Obtained for the Problem with Reduced Order Cost ($\alpha = 1, \beta = 25$)

	p-median			
p	**Initial obj. func.**	**Obj. func. (last)**	**Rand**	**Constructive**
1	3304638.935	3304638.935	3304638.935	3304638.935
2	3312121.691	3235529.436	3219296.053	3219296.053
3	3286299.969	3206245.797	3181096.140	3182111.152
4	3256407.915	3158354.108	3149180.670	3150096.075
5*	3262518.387	3127914.924	3127914.924	3130600.837
6	3307669.064	3188433.919	3163647.767	3166513.343
7	3346955.114	3239893.034	3203157.311	

Overall improvement with respect to p-median solution: %3.86

Computation time in seconds (p-median): 15
Computation time in seconds (random): 2503
Computation time in seconds (constructive): 38

p	Opened DC (p median)							Opened DC (random)							Opened DC (constructive)						
1	6							6							6						
2	6	38						6	80						6	80					
3	6	38	54					1	6	25					1	6	12				
4	1	3	54	71				1	6	25	54				1	6	25	54			
5*	1	3	25	54	71			1	3	25	54	71			1	3	25	54	71		
6	1	3	12	54	60	71		1	3	25	54	71	74		1	3	25	54	71	74	
7	1	10	12	32	54	60	71	1	3	25	54	71	74	78							

Cost composition (for the best objective function)			
shipping	**fixed**	**safety**	**order+ inv**
2195301.015	270223.000	542928.842	119462.066

APPENDIX F

THE RESULTS OF THE SENSITIVITY ANALYSIS FOR LOW VARIANCE LEVEL

Table F.1: Results Obtained for the Problem with Low Variance Level ($\alpha = 1, \beta = 1$)

	p-median			
p	**Initial obj. func.**	**Obj. func. (last)**	**Rand**	**Constructive**
1	3039901.063	3039901.063	3039901.063	3039901.063
2	2950877.962	2892513.312	2892513.312	2866758.324
3	2822442.190	2753191.846	2753191.846	2759350.554
4	2695604.628	2648735.045	2786699.212	2631135.820
5	2655599.973	2533821.534	2533821.534	2533821.534
6*	2657367.768	2536485.640	2688648.565	2532477.008
7	2654551.151	2546813.298	2608827.397	2542153.371
8	2624481.931	2566106.934	2629652.882	

Overall improvement with respect to p-median solution: %3.51

Computation time in seconds (p-median): 25
Computation time in seconds (random): 1752
Computation time in seconds (constructive): 37

p	**Opened DC (p median)**							**Opened DC (random)**							**Opened DC (constructive)**						
1	6							6							6						
2	6	38						6	80						6	80					
3	6	38	54					6	12	54					6	54	80				
4	2	3	54	71				1	6	12	54				1	6	12	54			
5	1	3	12	54	71			1	3	12	54	71			1	3	12	54	71		
6*	1	3	12	28	54	71		1	3	12	28	54	71		1	2	3	25	54	71	
7	1	10	12	28	32	54	71	1	10	12	28	32	54	71	1	2	3	25	28	54	71

Cost composition (for the best objective function)			
shipping	**fixed**	**safety**	**order+ inv**
2129830.560	312495.000	3018.547	87132.902

Table F.2: Results Obtained for the Problem with Low Variance Level ($\alpha = 1, \beta = 15$)

	p-median			
p	Initial obj. func.	Obj. func. (last)	Rand	Constructive
1	3163924.448	3163924.448	3163924.448	3163924.448
2	3125894.289	3062410.516	3036832.645	3036832.645
3	3037736.155	2966544.611	2941431.929	2960799.945
4	2943301.614	2890287.075	2864449.796	2868718.890
5*	2928508.703	2815178.145	2805214.636	2805620.289
6	2952246.508	2830081.259	2830081.259	2827947.921
7	2973812.915	2859345.458	2861986.796	

Overall improvement with respect to p-median solution: %4.21

Computation time in seconds (p-median): 15
Computation time in seconds (random): 1509
Computation time in seconds (constructive): 36

p	Opened DC (p median)							Opened DC (random)							Opened DC (constructive)						
1	6							6							6						
2	6	38						6	80						6	80					
3	6	38	54					6	54	80					1	6	12				
4	2	3	54	71				1	6	12	54				1	6	12	54			
5*	1	3	25	54	71			1	3	12	54	71			1	3	12	54	71		
6	1	3	12	28	54	71		1	3	12	28	54	71		1	3	12	25	54	71	

Cost composition (for the best objective function)			
shipping	fixed	safety	order+ inv
2173224.960	277024.000	42181.775	312783.901

Table F.3: Results Obtained for the Problem with Low Variance Level ($\alpha = 1, \beta = 25$)

	p-median			
p	Initial obj. func.	Obj. func. (last)	Rand	Constructive
1	3218705.614	3218705.614	3218705.614	3218705.614
2	3202601.204	3136714.001	3109737.995	3109737.995
3	3132377.559	3060232.823	3035377.114	3037250.467
4	3052567.463	2996308.418	2970805.444	2970805.444
5*	3048431.692	2932685.104	2924354.199	2932685.104
6	3081373.178	2958663.697	2958663.697	2951608.332
7	3113278.764	2996071.857	2997684.428	

Overall improvement with respect to p-median solution: %4.07

Computation time in seconds (p-median): 16
Computation time in seconds (random): 1642
Computation time in seconds (constructive): 27

p	Opened DC (p median)							Opened DC (random)							Opened DC (constructive)						
1	6							6							6						
2	6	38						6	12						6	12					
3	6	38	54					6	54	80					6	12	54				
4	2	3	54	71				1	6	12	54				1	6	12	54			
5*	1	3	12	54	71			1	3	12	54	71			1	3	25	54	71		
6	1	3	12	28	54	71		1	3	12	28	54	71		1	3	12	25	54	71	

Cost composition (for the best objective function)			
shipping	**fixed**	**safety**	**order+ inv**
2173224.960	277024.000	70302.958	403802.280

Table F.4: Results Obtained for the Problem with Low Variance Level ($\alpha = 1$, $\beta = 50$)

	p-median			
p	Initial obj. func.	Obj. func. (last)	Rand	Constructive
1	3328379.721	3328379.721	3328379.721	3328379.721
2	3355391.438	3284409.181	3250552.143	3250552.143
3	3321261.060	3247069.240	3219076.409	3219120.465
4	3271136.839	3208316.305	3182900.408	3182900.408
5*	3287201.253	3166678.642	3161785.270	3170172.448
6	3338800.910	3214540.120	3205446.664	3206187.200
7	3388861.646	3268163.395	3249842.997	

Overall improvement with respect to p-median solution: %4.21

Computation time in seconds (p-median): 15
Computation time in seconds (random): 1509
Computation time in seconds (constructive): 36

p	Opened DC (p median)							Opened DC (random)							Opened DC (constructive)						
1	6							6							6						
2	6	38						6	12						6	12					
3	6	38	54					6	12	54					6	12	54				
4	2	3	54	71				1	6	12	54				1	6	12	54			
5*	1	3	25	54	71			1	3	12	54	71			1	3	25	54	71		
6	1	3	12	28	54	71		1	3	12	54	71	74		1	2	3	25	54	71	

Cost composition (for the best objective function)			
shipping	**fixed**	**safety**	**order+ inv**
2174144.760	277024.000	140204.583	570411.927