

Inventory Positioning for a Multi-Echelon Distribution Network

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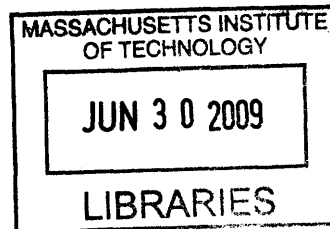
Submitted to the Engineering Systems Division in partial fulfillment of the requirements for the degree of

Master of Engineering in Logistics

at the

Massachusetts Institute of Technology

June 2009



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Abstract

This thesis presents a framework for deciding which products to centralize in a regional distribution center and which products to store decentralized close to the customer sites, for each facility in a multi-echelon distribution network. Our research specifically focuses on developing an optimization model to determine the inventory positioning strategy that minimizes total costs. The model considers both inbound and outbound transportation costs along with inventory holding costs at all facilities in the network. The total cost and responsiveness of the optimal solution are compared with the baseline network, in which inventory is completely decentralized.

Our analysis is performed using several products that have diverse characteristics, in terms of demand patterns, lead-times, product costs, service-level requirements, transportation modes, and supplier locations. A sensitivity analysis is performed to study how a variance in these parameters affects the optimal solution. The research suggests that for high volume commodity items the benefits of centralization are highly dependent upon the degree of lane consolidation. However, for low volume specialty items, centralization can provide immediate benefits with no change to the existing transportation network.

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1 Introduction

Our sponsor company, referred to as Company A, is a leading engineering services provider that performs a variety of services for its customers through a large network of suppliers and decentralized district distribution centers (DCs). The management of Company A is considering the option of centralizing some of the products needed for the services it provides to a few Regional Distribution Centers (RDC), each of which will serve the aggregate demand arising out of several district DCs. However, there are many complexities involved in deciding which products to centralize amongst a set of RDCs. These products have diverse characteristics, different demand patterns, distinct vendors, and unique service level requirements. The decision to centralize a product has a significant impact on total cost and responsiveness for company A. Choosing the optimal combination of RDCs, products, and district DCs requires an understanding of the trade-offs between inventory costs, transportation costs, and service levels. The objective of our research is to quantify these trade-offs and develop a decision-making framework to help Company A's management choose which products should be centralized to a RDC, and which products should be kept decentralized at the district DCs.

1.1 Problem Description

Company A maintains inventory for most of its products at the district DCs. However, for some products, holding inventory in a central facility that serves several district DCs can achieve a reduction in the total inventory and transportation costs. The elements of cost reduction can come through a) reduction in safety stock requirements due to the aggregation of demand variability (the risk-pooling effect), and b) reduction in supplier transportation

costs through a consolidation of replenishment orders across several district DCs. The reduction in costs has to be weighed against the effect on service levels and responsiveness to fluctuating demand.

With a highly decentralized structure, holding high inventory levels close to demand points (customer sites) is expensive, which provides an incentive to centralize and reduce total inventory. However, decentralization at the district DC provides higher responsiveness and service levels. Currently, company A faces this situation and wants to make a decision of centralization versus decentralization for some of its products. This decision needs to consider various factors for each product, such as:

- i) Demand volumes
- ii) Demand variability
- iii) Supplier lead times
- iv) Service levels
- v) Product responsiveness
- vi) Transportation mode and costs involved in on different lanes
- vii) Physical locations of suppliers, district DCs, and RDCs
- viii) Product characteristics
- ix) Operational constraints
- x) Annual purchase and delivery costs

Figure 1.1 shows how products flow from the suppliers through the RDC or the district DC to the customer site.

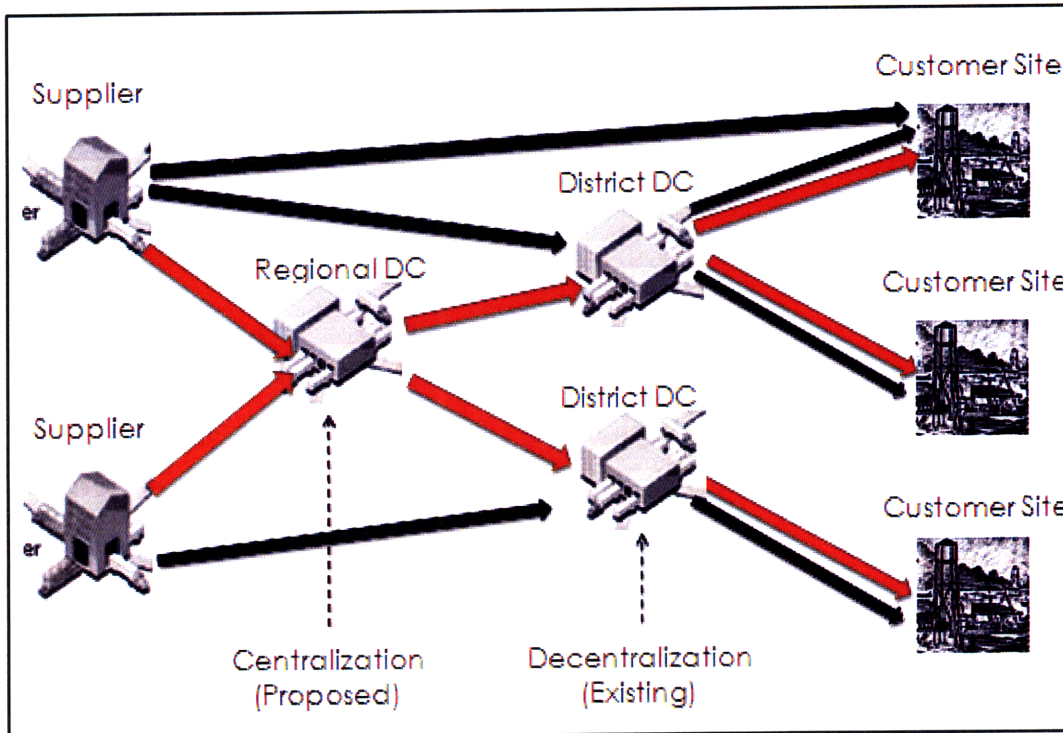


Figure 1.1: Flow of products in the distribution network

1.2 Background

Company A is a large engineering services firm, with a huge presence in North America including the United States. The company also has substantial presence in Europe and Asia. It has seen rapid growth over the past two decades and has expanded operations geographically, both outside and within the United States. The company offers technology-based products and services to its customers, who are large industrial corporations. Demand is driven by the unique needs of their customers. Company A submits bids for large heavy-engineering contracts and faces competition from several other firms offering similar services.

When the company initially set up its operations in the North American region, it predominantly operated in a decentralized manner. With a large number of district DCs setup close to customer sites the company has been able to meet the demand and sustain high service levels. This kind of decentralized operation could possibly lead to some inefficiency in the company's supply chain. In such a situation the company's management would like to review strategies that help them achieve higher operational efficiency. Inventory centralization is one such strategy the company wants to explore to study its effect on various operational aspects such as supply chain costs, inventory positioning, transportation costs and responsiveness to customer needs.

In order to understand the supply chain processes and policies used by our sponsor company, we conducted several interviews with executives and managers and made a site visit to one of their major distribution centers. In the following sections we discuss our interview process and give an overview of the distribution network and logistics operations that are currently in place at the company.

1.2.1 Interviews and Site Visit

Throughout this project we have interviewed several key executives, operations and category managers within the Logistics, Materials, and Procurement divisions of our sponsor company. The objective of these interviews was to develop a complete understanding of various aspects of product flow through the company's distribution network. These aspects included the business processes and systems involved in sourcing

and distributing these products, and the management objectives in terms of service level requirements and related metrics for different product categories.

In addition to the interviews, we also conducted a site visit to one of the largest district DCs that serves customer sites in the state of Texas. This visit was an important source of information as we were able to visually observe the various products, processes, and the end-to-end material flow from suppliers to the final customer sites. This greatly enhanced our understanding of the operations in the following aspects:

- i) Order placement and supplier relationships
- ii) The specialized storage techniques for different products
- iii) Capacity bottlenecks for bulk items and hazardous materials
- iv) The different transportation options used from district DC to customer sites
- v) Consumption patterns and business needs for different product categories
- vi) The penalty costs that are incurred in the event of a stockout of critical items

We also used this opportunity to interview one of the large volume commodity product suppliers and observed their operations. This shaped our understanding of the special storage and transportation needs of bulk products that are consumed in large quantities.

1.2.2 Distribution Network Overview

Company A distributes high volume commodity products and low volume specialty products in North America through a large network of decentralized district DCs. In this thesis we consider a subset of Company A's distribution network consisting of 30 product

variants that are distributed out of 15 district DCs to more than 3000 customer sites in one of the geographic regions of the United States. Figure 1.2 shows the physical locations of the district DCs and proposed regional DCs within the US Central region. Each district DC feeds a closely clustered group of customer sites. Figure 1.3 shows the number of distribution centers that serve a representative set of products. Products are delivered directly to the district DCs by a network of 30 vendors. In some cases multiple vendors are available to serve each product. Company A and its suppliers use both truck and rail modes of transport. A mix of contract carriers and private fleet are employed to move the products from the suppliers to the district and from the district to the customer sites. The company's distribution network is currently decentralized, with all products being held in the district DCs, which are close to the customer sites.

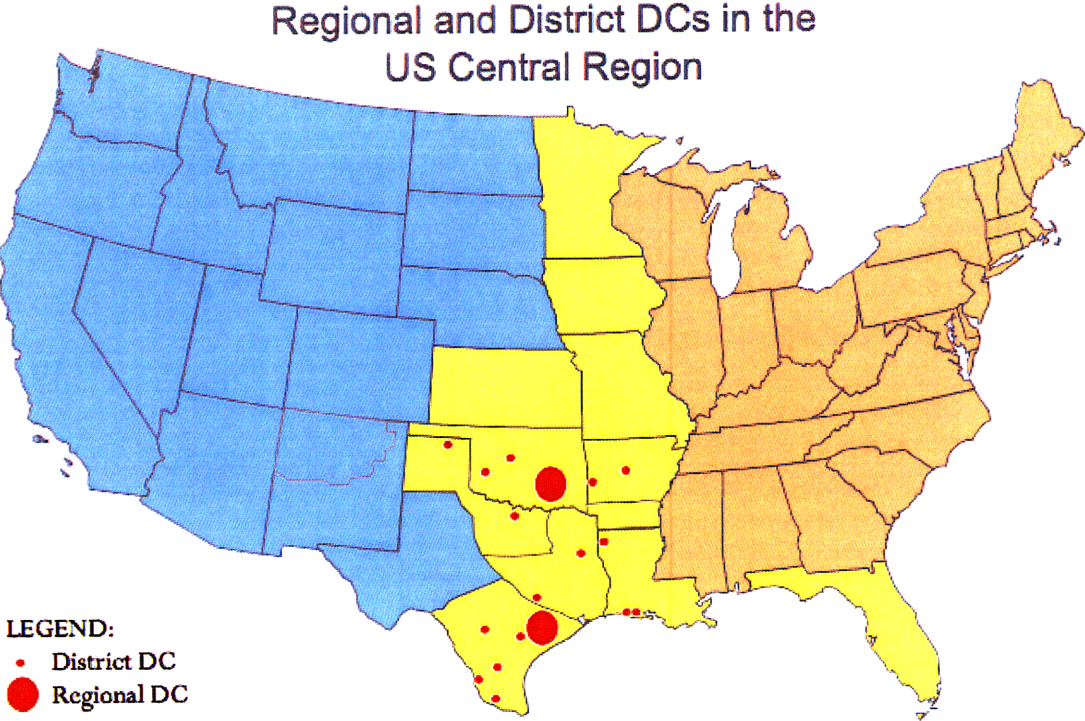


Figure 1.2: Physical locations of the district DCs

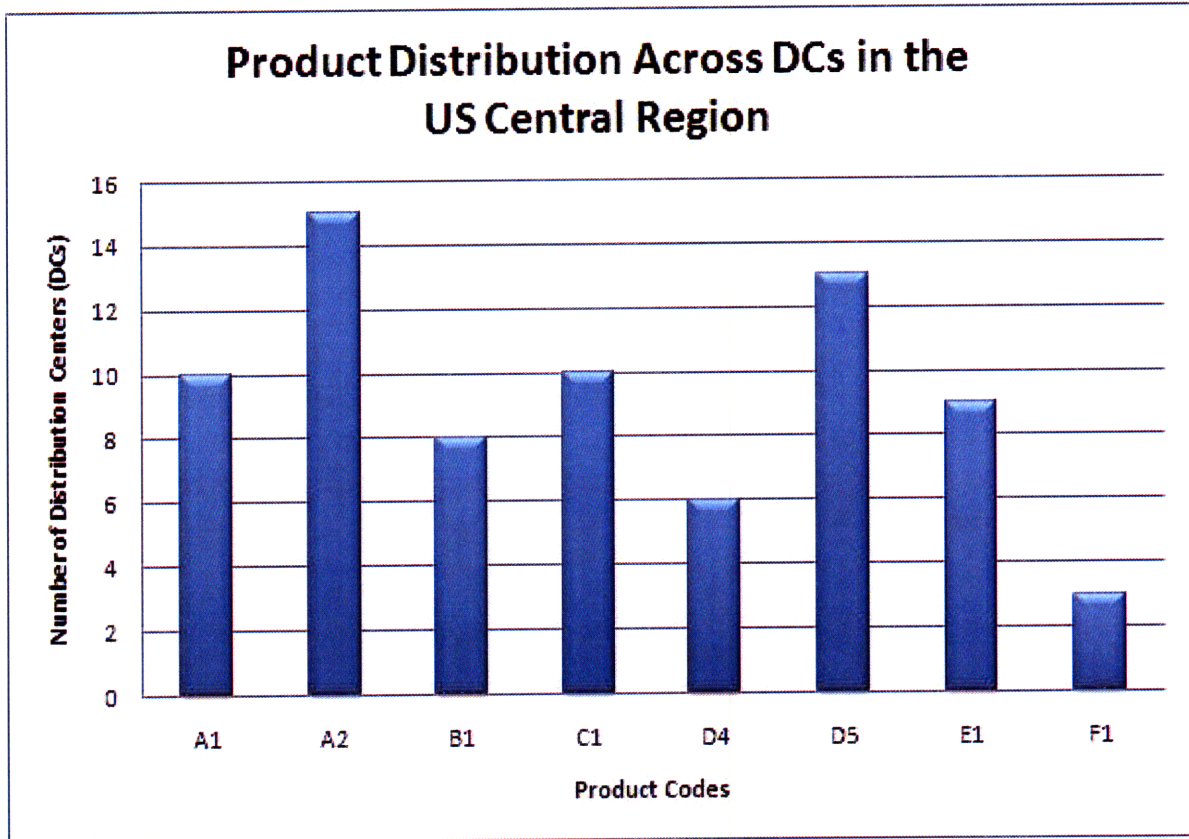


Figure 1.3: Distribution of the representative products in the US Central region

For our quantitative analysis we consider one product each from seven product families - A, B, C, D, E, F, and G spanning both specialty and commodity products. The annual volume in pounds is shown in the Figure 1.4. Demand attributes like standard deviation, average demand for each of the products are shown in Table 4.11 in Chapter 4. Figure 1.5 shows the annual dollar cost incurred for each product.

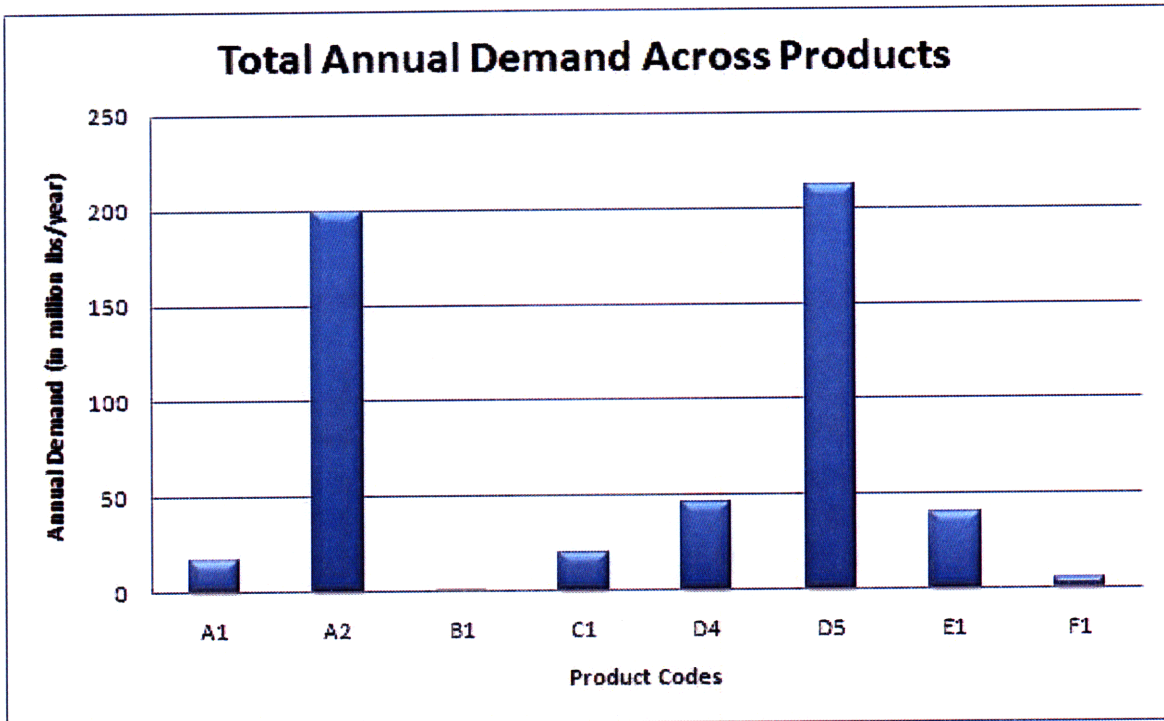


Figure 1.4: Annual product volumes across representative product set

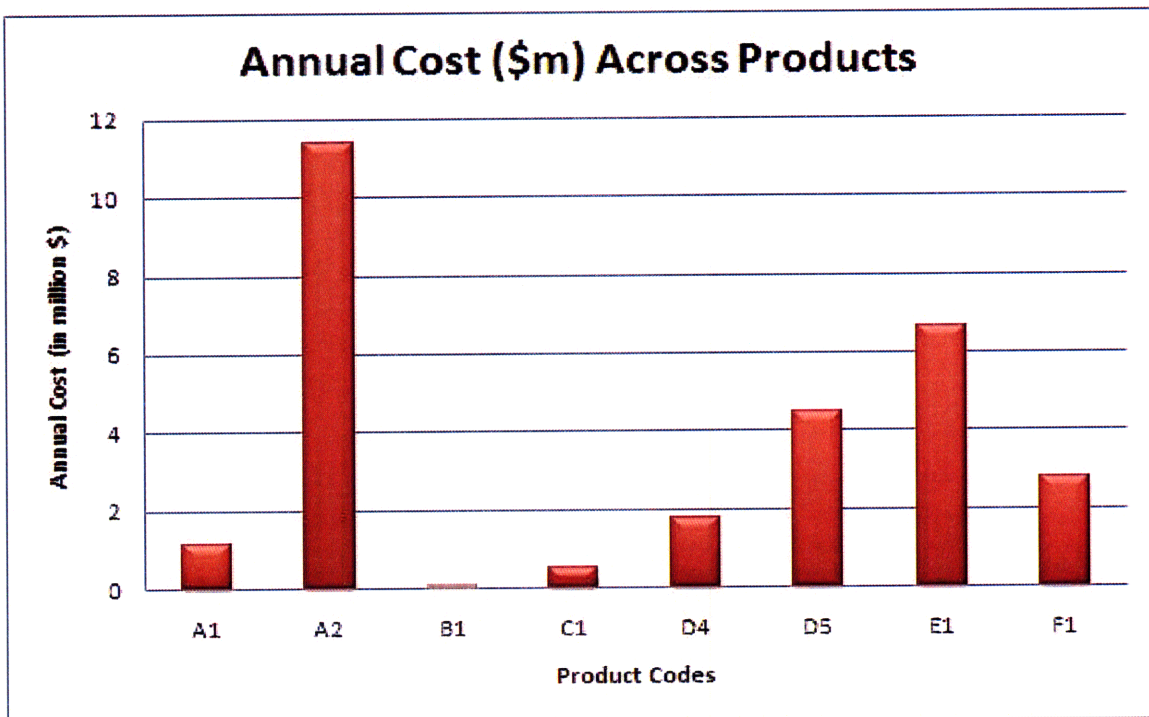


Figure 1.5: Annual cost of delivery across representative product set

1.2.3 Operational Overview

The current management structure and operations of Company A are heavily decentralized. Local decision-makers at each district DC are responsible for decisions of carrier selection for trucking, purchase order placement, and safety stock levels. In some cases the supplier relations are managed at a local level and in other cases at the central level.

At the facility we visited in Texas, orders for bulk items were placed on a weekly basis. Depending on the product and the transportation mode, the lead-time could be anywhere from four to fourteen days before product is delivered to the facility. When an order comes in from a customer, it is fulfilled directly from the district DC and material is consumed after the delivery. There are certain products that are classified as hazardous materials (Hazmat) and need special storage and treatment. In our discussions, the services managers at the district indicated a preference for moving storage of such materials to a centralized facility. This would reduce the risk associated with each local facility handling hazardous materials.

The district facilities have capacity limitations for some products, which therefore need to be stored in company-owned rail cars, silos, or private containers outside the facility. For certain products, the suppliers deliver the products to a terminal point, from which they are picked up by our sponsor company and delivered directly to the customer site where as for other products the district DCs sometimes process and then distribute them to the customer sites. A few products are also delivered directly to the customer site by the supplier. As

these products do not move through the district DC, they have not been included in our analysis.

1.3 Motivation

For our sponsor company it is very important to have the required product at the customer site when it is needed. Unavailability of a critical product can result in very high penalty costs, on the order of millions of dollars for each such event. This translates into a requirement of high service levels and high degree of responsiveness, which are currently achieved by storing all products close to the customer sites in the district DC. However, keeping inventory decentralized results in higher inventory costs. Aggregation of inventory would help Company A reduce the risk of demand variability thereby lowering inventory holding costs. Decentralized inventory also results in less efficient transportation from the supplier as different district plants order separately, and hence are unable to consolidate their orders into fewer shipments.

Company A's products have unique characteristics and service level requirements. For some products a high degree of responsiveness is critical, whereas for other products it is more important to get a lower total cost, within a specified service level tolerance. Currently inventory for all products is decentralized. A decision-making framework for centralization of inventory for some of Company A's products at a regional distribution center will give the firm the ability to make the best decision based on the trade-off between inventory costs and service level requirements for each product. Centralization will provide the company flexibility in choosing the appropriate inventory and transportation strategy that fit each

product's unique requirements. The potential benefits to Company A from inventory centralization are summarized below:

- i) Reduced aggregate inventory holding cost due to the pooling of demand variances across different district DCs
- ii) Consolidation of transportation costs from supplier to RDC due to larger order sizes, and less frequent orders
- iii) Lower transportation costs between RDC and district DCs is possible with high volume shipments on a private fleet
- iv) More economies of scale by centralized procurement from its suppliers
- v) Effective centralized transportation procurement and execution strategy
- vi) Simplified order processing and supplier relationships through centralized supply management

However, centralization also has costs associated with it, most notably the cost of reduced responsiveness to customer demand. In addition, it may be the case that for some products the volume being consumed by each individual district is so large that there is no substantial benefit of order consolidation across multiple districts. In such a case total transportation costs may even increase after centralization. The motivation for this project comes from the many benefits of centralization discussed above. These benefits have to be weighed against the costs of centralization, keeping in mind the business needs for each product.

1.4 Research Scope

This project involves the study of qualitative factors in conjunction with quantitative analysis for a set of representative products spanning seven product families. Our solution approach for making centralization decisions is based on finding the optimal inventory positioning strategy that minimizes total costs. It does not involve optimization of the physical locations of distribution centers as their locations are fixed. Our sponsor company has identified some of its existing district DCs to serve as central facilities (RDCs) in the future. Although the physical distribution network remains unchanged, we optimize the flow and storage of products within this network.

The final deliverable, for future use of Company A, consists of a tool through which the service level and total expected costs for inventory and transportation in the network can be quantified. Company A can use these outputs in conjunction with the qualitative analyses we provide to make decisions on centralization or decentralization of products. We also perform sensitivity analysis on product and system characteristics, which provides insights on the impact of variations in input parameters on the optimal solution, total costs, and supply chain responsiveness.

2 Review of Inventory Centralization Literature

Inventory centralization is useful when the costs of holding the safety stock form a large portion of the total system costs involved. In such a situation, centralization helps by reducing the effect of variability and decreasing the net safety stock costs in a distribution network. As we discussed in Chapter 1, our research problem focuses on optimally positioning inventory in a “multiple-warehouse multiple-retailer” (MWMR) kind of multi-echelon network. The first echelon in our network is the regional DC and the second is the district DC, as depicted in Figure 1.1. We approach the problem by surveying the research done in the multi-echelon inventory field based on analytical methods. We focus our research on the three research areas listed below:

- i) Inventory Pooling and Aggregation
- ii) Strategic Positioning of Inventory (Safety Stock)
- iii) Optimization-based Facility-Location Models

Inventory centralization literature (research areas i and ii above) typically focuses on finding optimal replenishment policies by minimizing inventory ordering and holding costs. Most authors assume the location of the facilities as fixed. By contrast, facility-location literature (research area iii above) has evolved around solving assignment problems for retailers to warehouses and around deciding the warehouse locations. Since our research problem encompasses both of these issues, we explore literature on both topics here.

2.1 Inventory Pooling and Aggregation

Eppen (1979) proposed a solution with respect to the decisions of centralization and decentralization of inventory. His paper provided insight into a multi-echelon problem with normally distributed demand at each location. He formulated the expected holding and penalty costs and demonstrated that these costs were lower in a centralized network compared to a decentralized network. These costs were dependant on demand characteristics such as variability and correlation. He also demonstrates the effect of demand correlation on the magnitude of savings achieved through centralization.

Zinn et al. (1989) explored the impact of sales correlation and its magnitude on the percentage reduction in safety stock inventory due to centralization. Here, the percentage reduction in safety stock due to centralization is determined without the standard assumption of identical demand variation at each stocking point. In our approach we use the “square root law” that Zinn et al. present for computing the safety stock cost. Assume that the annual demand variability at each demand point is represented by the standard deviation σ_i where i represents the demand point or retailer. The net inventory holding costs in a decentralized system would be represented by $C \sum_i^n \sigma_i$ where C represents a constant depending on the annual holding cost, the purchase price of the product and the lead time of replenishment from the supplier. In a centralized system, with no correlation across the demand points the net costs would be represented by $C \sqrt{\sum_i^n \sigma_i^2}$ where n is the number of demand points or retailers in the system. Thus the square root law clearly shows that “risk-pooling” or aggregation reduces the net inventory costs. The square root law is used in the context of

independent demand points at each of our district plants (demand is aggregated by customer sites). This formulation can be easily extended to cases where the demands are correlated.

Factors such as lead times of procurement, correlation across demand sites, and variability in demand are critical to our research problem. A study of literature spanning the effect of these three factors led us to the work performed by Caron and Marchet (1996). They developed an analytical approach to investigate the impact of these factors on the decision of centralization versus decentralization. They analyzed the level of aggregate safety stock level needed in a two-echelon system that consists of a central warehouse and remote warehouses (that in turn serve the end customer sites). In our analysis we use some of the qualitative factors considered by the authors that are similar to those faced by our client: number of remote warehouses in the system, proportion of demands served by central locations, and transportation costs involved between the central warehouse and decentralized warehouse. We use the analytical formulation developed by Caron and Marchet (1996) in our qualitative framework to understand the impact of these input factors on the decision of centralization. This formulation will be explained in detail in Chapter 3.

2.2 Strategic Positioning of Inventory (Safety Stock)

Strategic positioning of safety stock has been an important area of concern for managers as they look to reduce holding costs of safety stock in the supply chain and at the same time try to ensure that they meet required service levels. This is of importance in multi-echelon systems where these safety stocks act as buffers between stages to help each downstream stage meet their promised service level. Graves and Willems (2000) developed an

optimization-based framework for modeling strategic safety stock in a supply chain that is subject to demand or forecast uncertainty. The model was developed with the assumption that each stage of the supply chain quotes a guaranteed service time to its downstream customer, provided the external customer demand is bounded. They describe the successful implementation of their model at Eastman Kodak, where it helped increase service performance and reduce total supply chain inventory. This solution strategy determined safety stock levels but did not account for transportation costs or risk-pooling benefits of aggregating safety stock. Their main goal was to minimize the holding costs of the safety stock in the entire network subject to various product flow constraints through the different echelons.

In addition to the objectives of minimizing the inventory cost and transportation cost, responsiveness to customer needs must be considered as well. It is very difficult to quantify responsiveness by the number of stock-outs in an optimization model. Gaur and Ravindran (2006) proposed a measure for responsiveness as a product of the volume of a product that travels through the network from supplier to customer and the distance traveled. This measure is particularly important when we centralize inventory, as the ability of the whole network to meet any immediate needs at customer sites is reduced. Centralization pools inventory but at the same time increases the response time for meeting unexpected customer orders. While we develop an optimization model to minimize the inventory and transportation costs, the impact on the responsiveness of the supply chain, or the time taken by the product to reach the customer site, is also an important consideration.

2.3 Optimization-based Facility-Location Models

Existing literature on multi-echelon inventory theory has fewer models based on optimization, as compared to the ones based on heuristic methods. The complex nature of the problem and the inherent non-linearity in the formulations makes it difficult to solve optimization models by using standard non-linear solver algorithms. Das and Tyagi (1997) developed a non-linear integer programming model to measure the degree of centralization in a two echelon system with central warehouses and retailers. The non-linearity in the model is introduced by the square-root term in the formulation of the safety stock cost. They assume demand to be normally distributed. Their model incorporates safety stock costs, ordering costs, holding costs and transportation costs from the central warehouse to the retailer. This model is one of the first to incorporate the transportation costs between the warehouse and the retailer. The authors demonstrate the effect of transportation costs and required customer service level on the degree of centralization. Higher service levels and high transportation costs decrease the extent of centralization, whereas lower transportation cost favors centralization. Our optimization model uses their approach to build the safety stock and transportation cost elements. However, we extend the model further to include lane consolidation effects and transportation costs between the supplier and decentralized facility (district warehouses). These formulations are explained in detail in Chapter 3.

Daskin et al. (2006) developed a non-linear integer-programming model to solve a distribution center location problem by incorporating the safety stock and cycle stock costs at the distribution centers. The authors considered a three-echelon system consisting of suppliers, warehouses, and retailers. They also incorporated the transportation cost between

the supplier and the central warehouses to show the benefit of economies of scale achieved in the fixed cost incurred at the suppliers. They propose a lagrangian relaxation algorithm to solve the problem. Their initial formulation used a uniform ordering policy based total cost that helped determine the optimal number of replenishments. They further extended this approach to formulate an assignment problem (retailers to warehouses) using the optimal number of replenishments computed in the initial step.

We formulate a three-echelon model, similar to the one developed by Daskin et al. (2006), but with two important variations. Firstly, we allow inventory stocking at the decentralized warehouses (retailers) in our network. We model the transportation costs incurred from the supplier to both decentralized and centralized warehouses. Secondly, we ignore the cycle stock costs in our network, since Company A would incur the same cycle stock costs in a centralized or decentralized network. As we compare the costs of operating a centralized versus decentralized network in our model the cycle stock costs will not affect our solution.

The objectives of determining an optimal replenishment policy by minimizing the total system costs and determining the best configuration (assignment and location) of warehouses and retailers are conflicting in nature. A warehouse-location problem is solved to ensure minimal transportation costs and maximize responsiveness, whereas an optimal replenishment policy would tend to lower the inventory costs by aggregation and hence reduce the responsiveness of the supply chain. The research by Gaur and Ravindran (2006), mentioned in Section 2.2, develops a two-step process based on optimization models to solve this conflicting problem. The first step solved the assignment of retailers to

warehouses as well as the optimal positioning of warehouses. The second step determined an optimal replenishment policy by minimizing total system costs that include inventory costs, transportation costs, facility costs and setup costs. The first step was based on a linear program and the second was based on a non-linear program. They also accounted for the variability in lead times and the demand faced by the retailers in the second step. The final decision was made by analyzing a series of possible configurations with a different set of warehouse locations, total system cost and measure of responsiveness. This kind of a multiple criteria model is extremely effective for managers facing the dilemma of positioning warehouses and inventory in their supply chains. We use a similar approach to factor various qualitative considerations along with the safety stock costs, transportation costs and product responsiveness in making the final decision on centralizing a product.

Currently in our sponsor company's operational network, inventory can be either centralized (at the RDC) or decentralized (at the district DC). The transportation costs between the RDC and the district DC and between the supplier and district DC are critical to the decision of centralizing a product. We develop a non-linear integer-programming model by incorporating safety stock costs of holding inventory at the RDC and the district DC along with the transportation costs incurred in delivering the products to the district DC. In Chapter 3 we describe our model in detail and explain the various assumptions, cost elements and constraints of our optimization model.

3 Methodology

In this chapter we address the key question that our sponsor company is facing: how should management decide which products should be centralized, and which products should remain at the district DC? We attempt to answer this question by building an optimization model that will take each product and evaluate the total cost comprising the costs of inventory and transportation in both centralized and decentralized scenarios. The total cost function is then minimized, subject to the constraint that a district DC cannot be served by multiple central facilities. This optimization model is run on a product-by-product basis. The output of each run will tell which district DCs should centralize the product and which should not, in order to obtain a least-cost configuration. Thus the centralization decision is made separately for each product at each district DC. We further generalize our quantitative results to make quick decisions for other products within the same product families.

3.1 Model Description

In this section we describe our model for making the inventory centralization decision for a given distribution network. As discussed in Chapter 2, our model builds on the work done by Das and Tyagi (1997). However, there is a significant difference between their distribution network model and ours. They consider all end customer demand as being met only from the central facilities, and therefore as they move from decentralization to centralization, the total number of facilities in their model reduces. In our model we will consider a constant number of facilities serving customer demand. One central facility could serve several district DCs' aggregated customer demand. The end customers are always served through the district DC only. Our model is based on the assessment of actual

requirements and existing distribution network setup at Company A, and hence does not propose to change the location of the central facilities.

When a product is centralized it means that the product is stored in the central facility, but it will still flow through the district DC when end customer demand arises. So cycle stock will always move through both facilities, but safety stock will be kept only at one of the two echelons. The benefit of distributing a product that is centralized through a district DC is that it enables consolidation of transportation costs between the central and district facilities. This is because the end customers are mostly clustered around each district DC. The network can be represented as shown in Figure 3.1.

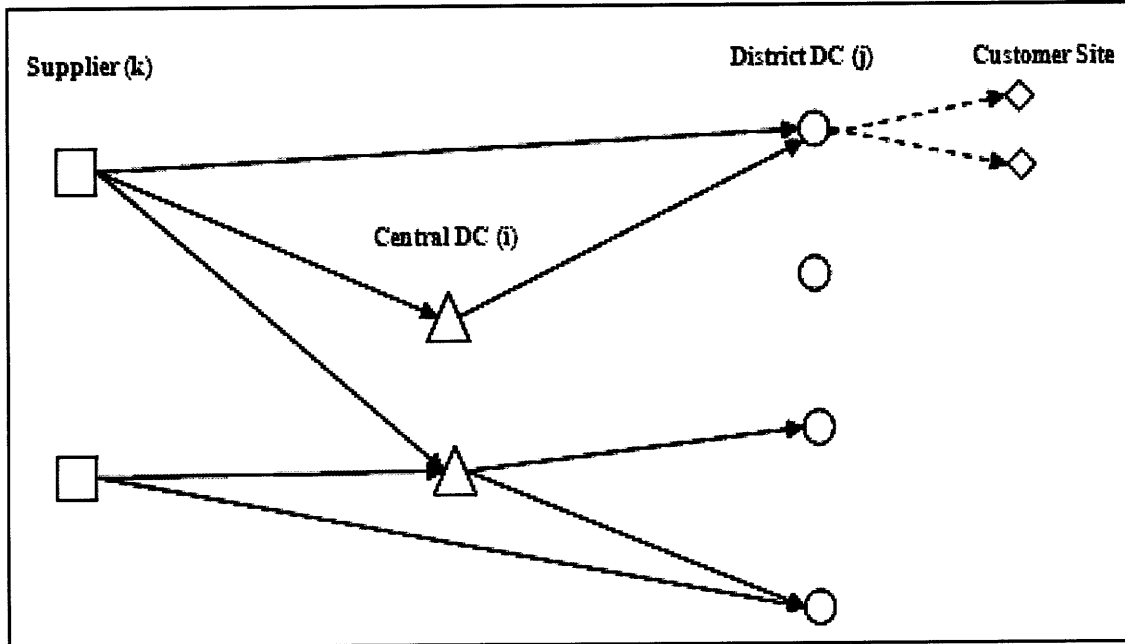


Figure 3.1: Representation of distribution network

The terms t_{ki} on the three arcs above represent the transportation cost per unit weight and per unit distance.

3.2 Assumptions

Our model assumes customer demand at each district DC to be normally distributed with a known mean and variance. This assumption is common in literature and allows us to integrate the stochastic demand directly into our model. The demand at each central facility is computed based on the total demand of all districts that it serves. The variance of demand at the central facility will typically be less than the variance at each individual district DC, due to pooling of the demand variance from each district. As described in Section 2.1, this effect is known as the “square-root law”. In building this model we assume independent demand at each district DC. However, it would not be difficult to extend this model to account for demand correlation.

We also assume that all facilities use a base-stock inventory policy to order replenishments, which means that they use an order-up-to level for each product and periodic-review. This is a realistic assumption and is based on our interviews with the services managers at Company A. For the purpose of analysis we neglect the inventory in transit while formulating the cost elements, since in steady-state those volumes do not change and thus do not impact the decision. The central and district facilities both order from the suppliers. The lead time from the suppliers to the various RDCs and district DCs is known and assumed to be constant in our model. The district facilities can also order from the central facility, which has a different lead time. Lead times are assumed to be deterministic and constant from all suppliers. Again, it is possible to extend the model to incorporate variable lead times. Our model does not consider capacity constraints, and hence assumes that

suppliers will be able to meet demand, and Company A will have the physical space to store the required quantity of product.

Finally, we assume that a single district DC will either be completely centralized or completely decentralized for a given product; hence there is no partial centralization at any given district facility. Each of these assumptions was discussed with our sponsor company in order to make the model as valid as possible.

3.3 Cost Elements

Our model incorporates the following costs elements: Safety Stock Cost, Outbound Transportation Cost, and Inbound (Supplier) Transportation Cost. The optimization run will evaluate all the cost elements collectively in both centralized and decentralized scenarios to determine the optimal configuration. The configuration comprises all the suppliers and all selected facilities where the product is stocked. Each of the cost elements will have an individual impact on the centralization decision, and the tradeoff will be made by analyzing which configuration results in the lowest total cost for each product.

- i) **Safety Stock Cost:** This is the cost of holding safety stock to cover for uncertainty in demand or supply. The safety stock for a particular product held at any facility will depend on the variance of demand from its customers, the service level required, and the lead-time from suppliers. The effect of service levels will be captured in the safety stock cost. An increase in service level will increase the required level of safety stock.

- ii) **Outbound Transportation Cost:** This is the cost of transportation that is borne by company A. When the product is centralized, transportation cost will involve the cost of transporting the product from central facility to the district DC, and from the district DC to the end customers. When the product is decentralized, transportation cost will involve cost of transporting the product from district DC to the end customers. As we can see, the second leg (from district DC to end customers) is common to both options. Hence for the purpose of comparison between the two options we will only consider the first leg (between central and district DC) for our analysis.
- iii) **Inbound (Supplier) Transportation Cost:** This will account for the cost of transportation from the suppliers to the central facility (in the case of centralization) or to the district DC (in the case of decentralization). When a product is centralized there may be significant savings in supply costs due to transportation consolidation between the supplier and the central DC. Centralization can also result in savings due to other factors, such as reduction in administrative and overhead costs of maintaining supplier relations at each district DC, and less frequent replenishments from the supplier. Although this cost is borne by the supplier, any significant savings to the supplier can be used to negotiate lower product cost, and hence can be passed on down the supply chain. In our model we use a reduction factor, M , to denote a percentage reduction in inbound (supplier) costs due to consolidation. M will depend

on the consolidation of replenishment orders placed to the supplier after centralization.

We do not consider the Cycle Stock Cost, because in a base-stock ordering system, this cost would be the same irrespective of whether we choose to keep the inventory centralized or decentralized. The Order Cost would depend on the number of replenishment orders placed in both scenarios and on the lane capacities from the various suppliers to our sponsor company's facilities. We do not directly include Order Costs in our model. However, we do estimate a "reduction factor" based on lane capacities that is explained in more detail in the next section.

3.4 Model Formulation

The notation and equations used to build the model are shown below. We first describe general notation that is used for both centralization and decentralization. Then we present the equations used to build the cost elements for both scenarios separately.

3.4.1 Notation

$x_{ij} = 1$ if central facility i is assigned to district DC j ; 0 otherwise

r = holding (carrying) cost of inventory at any echelon

v = purchase cost of a given product from the supplier

$(1 - \alpha)$ = desired service level at the district DC

Z_α = z-value of standard normal distribution corresponding to service level

N = number of days in a year that demand occurs for the product

m = number of suppliers serving a given product

M = consolidation supplier cost reduction factor

3.4.2 Cost Elements for Decentralization

L_{kj} = Lead-time in days between supplier k and district DC j

t_{kj} = unit cost of transportation from supplier k to district DC j

d_{kj} = distance in miles from supplier k to district DC j

D_j = daily demand for a particular product at the district DC j

The expected value and variance of daily demand at the district DCs are given by:

$$E(D_j) = \mu_j$$

$$Var(D_j) = \sigma_j^2$$

i) Annual Safety Stock Cost

$$SS_j = rvZ_\alpha\sqrt{L_{kj}}(\sum_j \sigma_j) \cdot (1 - \sum_i x_{ij}) \quad (3.1)$$

The safety cost that is required to cover for demand variation and for lead-time from

supplier k to district DC j is given by $Z_\alpha\sqrt{L_{kj}} \sum_j \sqrt{Var(D_j)}$ (Das and Tyagi, 1997). We

multiply it by the term rv to account for the cost of holding the safety stock. The term Z_α

takes into consideration the service level required, given the penalty and holding costs. We

also multiply this expression by the term $(1 - \sum_i x_{ij})$, which will be equal to 1 in the case of

decentralization, and equal to 0 in the case of centralization for a particular district DC under consideration.

ii) Annual Outbound Transportation Cost

$$TC_j = \text{zero} \tag{3.2}$$

The supplier delivers directly to the district DC in the case of decentralization, so our sponsor company does not incur any cost of transportation. As explained in the previous section, we ignore the second leg (from district DC to each individual work site) because that leg is common to both centralization and decentralization and hence will not impact our decision.

iii) Annual Inbound (Supplier) Transportation Cost

$$SC_j = N \sum_k \sum_j (1 - \sum_i x_{ij}) \frac{\mu_j}{m} d_{kj} t_{kj} \tag{3.3}$$

The cost to supplier k of serving a particular district DC j is given by $\frac{\mu_j}{m} d_{kj} t_{kj}$. We have divided μ_j by m to distribute the total volume over m suppliers. This is multiplied by the term $(1 - \sum_i x_{ij})$, which will be equal to 1 in the case of decentralization, and equal to 0 in the case of centralization. The summations over k and j are done to include this cost element for all suppliers serving all district DCs for a particular product. The multiplication by N is done to convert daily cost to annual.

3.4.3 Cost Elements for Centralization

L_{ki} = Lead-time between supplier k and central facility i

t_{ij} = unit cost of transportation from central facility i to district DC j

t_{ki} = unit cost of transportation from supplier k to central facility i

d_{ij} = distance in miles from central facility i to district DC j

d_{ki} = distance in miles from supplier k to central facility i

D_i = aggregate daily demand for a particular product at the central facility i

The expected value and the variance of daily demand at the central facility is given by

$$E(D_i) = \sum_j x_{ij} \mu_j$$

$$Var(D_i) = \sum_j x_{ij} \sigma_j^2$$

i) Annual Safety Stock Cost

$$SS_i = rvZ_{\alpha} \sqrt{L_{ki}} \sum_i \sqrt{Var(D_i)} = rvZ_{\alpha} \sqrt{L_{ki}} \sum_i \sqrt{\sum_j x_{ij} \sigma_j^2} \quad (3.4)$$

The main terms of this cost element are the same as for the decentralized case. The difference is that the variance is multiplied by x_{ij} , which will be 1 for centralization and 0 for decentralization. This element is a non-linear (concave) increasing function of x_{ij} (Das and Tyagi, 1997).

ii) Annual Outbound Transportation Cost

$$TC_i = N \sum_i \sum_j x_{ij} \mu_j d_{ij} t_{ij} \quad (3.5)$$

The cost to our sponsor company of serving district DC j from central facility i is given by $\mu_j d_{ij} t_{kj}$. This is multiplied by x_{ij} , which will be 1 for centralization and 0 for decentralization. The summation over i and j will incorporate this cost element over all

central facilities serving a particular product to any district DC. The multiplication by N is done to convert daily cost to annual.

iii) Annual Inbound (Supplier) Transportation Cost

$$SC_i = N \sum_k \sum_i M(t_{ki} d_{ki} \sum_j (x_{ij} \frac{\mu_j}{m})) \quad (3.6)$$

The cost to the supplier k for serving the central facility i is given by $t_{ki} d_{ki} \sum_j x_{ij} \frac{\mu_j}{m}$. This is multiplied by an estimated reduction factor, M , that will depend on the consolidation in the number of replenishment orders placed per year after centralizing a product. The multiplier M will be an input to the optimization model and can be changed as required. M is estimated by using the total annual demand and lane capacities for each supplier to DC leg to compute the expected number of replenishment orders. The difference in the expected number of replenishment orders for complete centralization and complete decentralization is then used to determine the maximum possible reduction percentage. The actual value of M may be less than this, and different values have been used to test the sensitivity of the model to variation in M .

3.4.4 Problem Formulation

In this section we use the cost equations described above to build the objective function for our optimization model. The decision variable, objective function and constraints are described below.

i) Decision Variables

The decision variables are the terms x_{ij} , where

$x_{ij} = 1$ means that product at district DC j should be centralized at facility i

$x_{ij} = 0$ means that product should remain decentralized at district DC j

ii) Objective Function

Minimize total cost = (total cost of decentralization) + (total cost of centralization)

$$= (SS_j + TC_j + SC_j) \quad + (SS_i + TC_i + SC_i)$$

The objective function is non-linear with respect to the Safety Stock Cost at the centralized locations (SS_i) because of the square root term involved.

iii) Constraints

The model is subject to the following constraints.

- a. Each district DC is served by at most one central facility

$$\sum_i x_{ij} \leq 1 \quad \text{for all } j$$

- b. Each district DC is either assigned to a central facility (1) or is not assigned to any central facility (0)

$$x_{ij} = 0 \text{ or } 1 \quad \text{for all } i, j$$

This model is implemented in Microsoft Excel 2007 using the commercially available solver “What’sBest! 9.0.3.6” by Lindo Systems, Inc.

3.5 Data Analysis for Model Inputs

In the previous section we gave a detailed explanation of our model formulation. The model requires several inputs, such as demand patterns, unit purchase prices, lead-times,

transportation multipliers, and distances. Here we outline the data analysis that was performed to convert several files of raw data, which we received from our sponsor company, into the input data for our model. All of the data we received was for the year 2007. The major data inputs that were used for our analysis include:

- i) Monthly consumption data for each product at every district DC in our sponsor companies distribution network.
- ii) Transactional purchase order and invoice information for all orders placed from the district DCs to their vendors.
- iii) Physical location of all vendors and facilities in the distribution network.
- iv) Transportation costs between the vendors and the district DC.

Each data file required significant analyses and manipulation to extract the required inputs from the raw data. The major data analysis steps we performed were:

- i) We used the purchase order information to determine the unique vendors that served each product to each district DC. This was done by aggregating the transactional orders to unique combinations of product, district, and vendor.
- ii) The purchase order and invoice creation dates were used to determine the lead-times for each product between its vendor and the district DC. They were also used to establish the average purchase price for each product.
- iii) The monthly consumption data at the district DCs was used to determine the demand patterns for each individual product. We computed the mean and standard deviation for each product and analyzed the demand distribution.

- iv) The physical location of vendors and district DCs enabled the calculation of distances between all nodes in the network. This calculation involved first determining the latitude and longitude of each location and then using a point-to-point distance formula to calculate the actual distances. The distance formula we used calculates the straight line distance between any two locations.
- v) Transportation costs on different lanes in the network were used to establish the base values of our transportation multipliers on the three legs in our network.

The data analysis described above was performed in Microsoft Excel 2007. This processing of raw data is essential to prepare the inputs that are required for our model.

4 Interpretation of Results

In the previous chapter, we described in detail our solution approach and the formulation of our optimization model. Appendix A lists the results for a representative set of products. Appendix B explains the implementation of this model in Microsoft Excel along with user instructions. In this chapter we describe the model outputs and an interpretation of our results. Our analysis was done using several products that have diverse characteristics, in terms of demand patterns, lead-times, product costs, service-level requirements, transportation modes, and supplier locations. The products, provided by our sponsor company, include high volume commodity items and low volume specialty items. We have chosen a set of representative products across seven product families, for which our sponsor company needs to decide whether to centralize or decentralize inventory

In Section 4.1 we illustrate the use of our model and provide an interpretation of the results for one particular product. We also provide detailed quantitative results for seven other products in Appendix A. In Section 4.2 we discuss the qualitative extension of our results to the remaining set of products. As we run the representative set through our model, we generalize some conclusions drawn from their quantitative analyses to the larger set of products. For each product we provide guidance on whether to centralize inventory at the RDC, or leave it decentralized at the district warehouse.

4.1 Quantitative Analysis

4.1.1 Model Setup

The optimization model is run for each product, one at a time, after specifying all relevant inputs and product characteristics. The output is an optimal configuration that represents the best possible placement of inventory in the given network in order to minimize costs. The results indicate the total costs of the optimized network, along with a measure of supply chain responsiveness. Total cost is the sum of the expected inventory and transportation costs. Responsiveness is measured in terms of product miles, which is the product of annual volume and distance traveled for any product. Higher product miles indicate lower responsiveness, and vice versa. Table 4.1 shows the input demand attributes for product A1. Clearly the mean and standard deviation of demand vary greatly across the districts DCs.

Table 4.1: Demand attributes for product A1

Demand Attribute	2050	2051	2055	2056	2058	2059	2061	2062
Average Demand (lbs/day)	4637	1110	1834	2506	12434	9540	1982	4384
Standard Deviation (lbs/day)	9482	387	5309	17141	44331	21645	8026	7283

Sections 4.1.2 and 4.1.3 describe the different types of analyses done on each product. We describe the baseline scenario, the optimized scenario and details of sensitivity analysis. Appendix A contains the detailed results for a representative set of products following the format below.

4.1.2 *Baseline Scenario*

The baseline scenario is one where the products are completely decentralized and represents the current operational setup at our sponsor company. The baseline cost is the sum of the net transportation costs from supplier to district DCs and the cost of holding safety stock at these facilities. The optimal solution is compared with the baseline cost to compute the annual savings. We see a range of savings from 0% to 10% over the total costs, typically ranging from \$1 million to \$12 million per year, for our representative set of products. We also compared the product miles in the baseline and optimized scenario and observed that it can increase up to 14% over the baseline scenario. The product miles typically increase with higher degree of centralization.

4.1.3 *Optimized Scenario*

The optimized scenario represents the best possible placement of inventory in a given network based on the aggregated demands at the district plants and the various input parameters. This is the least-cost configuration based on the results provided by LINDO 9.0's non-linear global solver. A snapshot of the output for product A1 is shown below in Tables 4.2, 4.3 and 4.4.

Table 4.2: Snapshot of optimization run results

Optimization Run Results				
No	Description	Units	Centralized	De-Centralized
1	Total Number of District Plants Cen	#	\$ 4	\$ 4
2	Aggregate Safety Stock Cost	\$/year	\$ 5,419	\$ 19,605
3	Aggregate Transportation Cost	\$/year	\$ 79,196	\$ 147,627
4	Total Product Miles Traveled	lbs-miles	8,944,521	

Table 4.3: Comparison of baseline and optimized scenarios

Baseline Cost Comparison

No	Description	Units	Baseline	Optimized	% change
1	Aggregate Safety Stock Cost	\$/year	\$ 29,366	\$ 25,024	-15%
2	Aggregate Transportation Cost	\$/year	\$ 231,469	\$ 226,823	-2%
3	Product Miles	lbs-miles	9,059,439	8,944,521	-1%

Table 4.4: Assignment of districts to RDCs

RDCs	District Plants								
	2050	2051	2055	2056	2058	2059	2061	2062	
2052	0	0	1	1	0	0	1	1	
2057	0	0	0	0	0	0	0	0	

Table 4.4 shows the result of our optimization run for a given set of base inputs. The 1's in the figure represent centralization by an assignment of district plants to an RDC. The 0's represent decentralization at the district DC. Thus districts 2055, 2056, 2061 and 2062 should centralize product A1 to RDC 2052 in order to minimize total costs. Districts 2050, 2051, 2058 and 2059 should keep product A1 decentralized. RDC 2057 is not assigned product A1 from any of the district DCs; this is logical, since RDC 2057 is further than RDC 2052 from the district plants in this data set.

4.1.4 Sensitivity Analysis

We consider seven product families that consist of low volume specialty products and high volume commodity products. Table 4.11 at the end of this chapter lists the important characteristics of each product. In this section we present the sensitivity analysis done for one such product, A1, from a high volume commodity product family. We test the

sensitivity of the solution to six different input parameters to demonstrate their impact on the behavior of the model.

In the graphs shown for the six cases of sensitivity analyses, the vertical line named “base input” represents the optimized scenario discussed in Section 4.1.3 (not to be confused with the “baseline” on the left axis, where all district DCs are completely decentralized). The points of intersection with the three curves (red, blue and green) represent the outputs for the base case. We also show the percentages on the red line (total costs) and the blue line (product miles) that depict the sensitivity of the cost variable and product-miles to the variation in one of the inputs parameters.

i) Effect of Transportation Reduction Factor due to Lane Consolidation

We perform a sensitivity analysis of the optimal solution with respect to the reduction factor, M , which we had set to 25% in our base input. Recall that M accounts for the percentage of lane consolidation in supplier shipments when the product is centralized. The intent of this analysis is to gauge how the optimal solution will change with variation in lane consolidation after centralization. To perform this sensitivity test we vary M from 0% to 60% in steps of 5% each, and run the optimization model repeatedly keeping all other inputs the same. The results are shown in Figure 4.1 and Table 4.5 below.

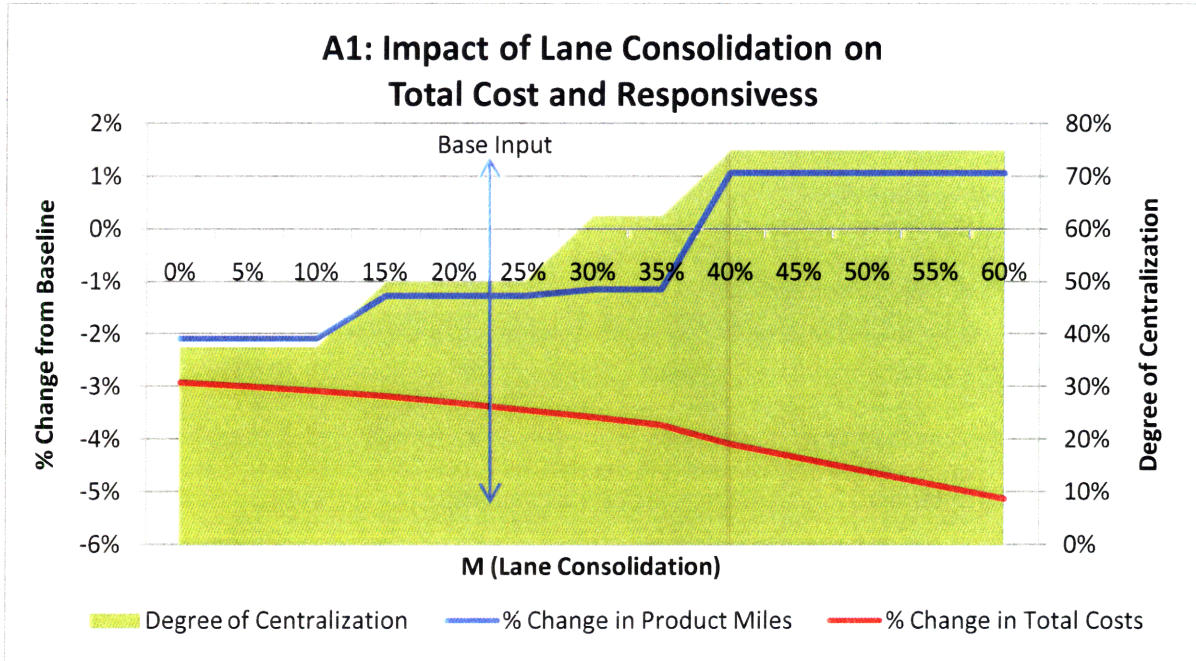


Figure 4.1: Sensitivity analysis for lane consolidation

Table 4.5: Sensitivity analysis table for lane consolidation

Scenario	Lane Consolidation	Degree of Centralization	Total Cost	Product Miles
Low	5%	38%	\$ 252,996	8,869,993
Base Value	25%	50%	\$ 251,847	8,944,521
High	50%	75%	\$ 248,814	9,155,959

Figure 4.1 shows that as the lane consolidation increases, the degree of centralization (the percentage of district DCs that are now centralized) in the optimal solution also increases (shown by the shaded green area). This means that a higher number of district DCs would get centralized for a product if we had a higher consolidation opportunity on the supplier to RDC leg. With an increase in centralization, the total costs reduce and the product miles increase. Thus, we can clearly see the tradeoff between total cost and responsiveness. As the lane consolidation increases, fewer replenishments are sent to the RDC to meet the annual

demand, which translates to a large reduction in the inbound transportation costs. The total miles traveled by the product also increase, which is the cause of reduced responsiveness.

ii) Impact of Transportation Multiplier

Here we perform a sensitivity analysis of the optimal solution with respect to the transportation cost multiplier, T_{ij} . The intent of this analysis is to gauge how the optimal solution will change with variation in transportation costs between the RDC and district DCs. To perform this sensitivity test, we varied T_{ij} in a 70% band above and below our base input of 0.0066 cents/lb/mile. The optimization model was run repeatedly for each input of T_{ij} keeping all other inputs constant. The result is shown in Figure 4.2 and Table 4.6 below.

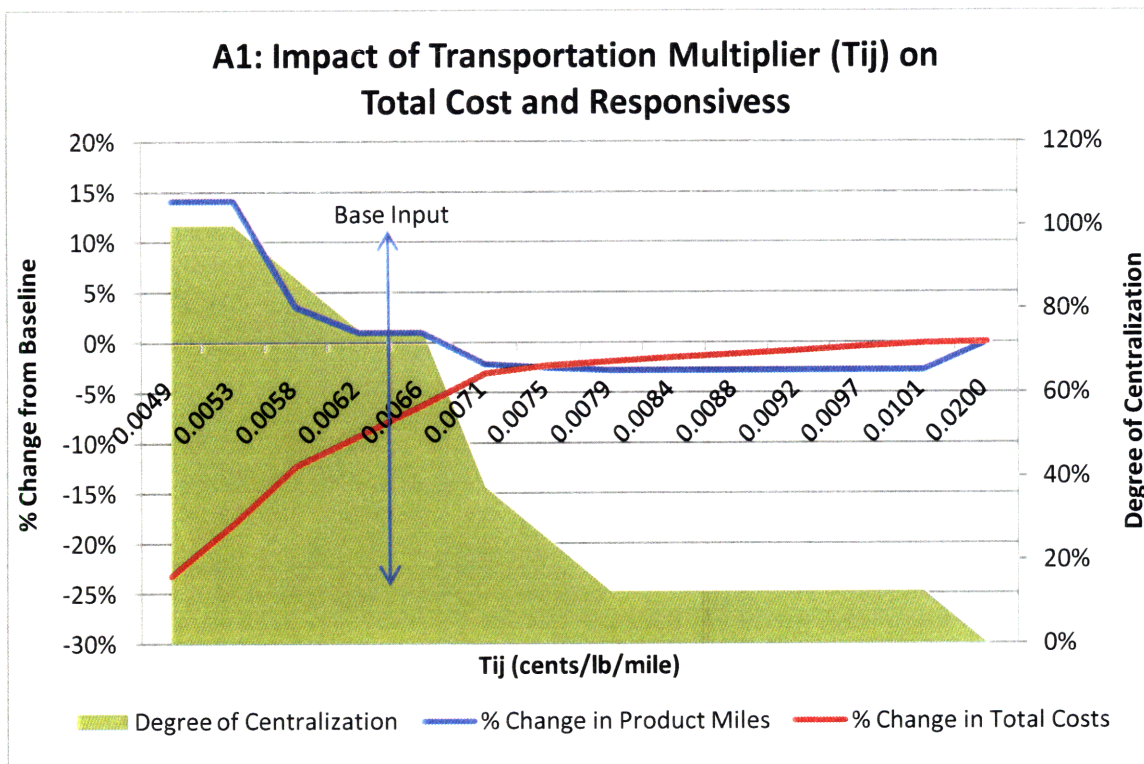


Figure 4.2: Sensitivity analysis for transportation multiplier T_{ij}

Table 4.6: Sensitivity analysis table for T_{ij}

Scenario	Transportation Multiplier	Degree of Centralization	Total Cost	Product Miles
Low	0.0053	100%	\$ 213,934	10,340,547
Base Value	0.0066	75%	\$ 244,480	9,155,959
High	0.0088	13%	\$ 257,767	8,811,361

Figure 4.2 shows that as the transportation multiplier T_{ij} increases, centralization becomes less attractive. This also makes sense intuitively because the transportation cost between RDC and district is incurred only in the case of centralization. Increasing this cost should therefore reduce the degree of centralization, and we can see from the graph that as T_{ij} increases to 0.020 cents/lb/mile the optimal solution is completely decentralized. The graph gives further insight that as T_{ij} increases, total costs will increase due to decentralization and the supply chain will become more responsive.

iii) Effect of Service Level on Total Costs and Degree of Centralization

The district DCs serve the customers demands. The perceived service level by the customer is related to the probability of not meeting demand. Either the central or the district DC would handle the service level in a similar manner since the customer is unaware of where the inventory is actually stocked. The service level drives the safety stock cost. Hence, the higher the required service level, the higher the safety stock cost, which drives a preference for centralization. We vary the service levels between 94% and 99.9% to see the effect on the safety stock cost and the total system cost. We notice that the effect on safety stock cost can be substantial if the purchase price is very high or if there are high lead times. In other cases the effect is very small and in such cases centralization is beneficial only if there exist lane consolidation opportunities.

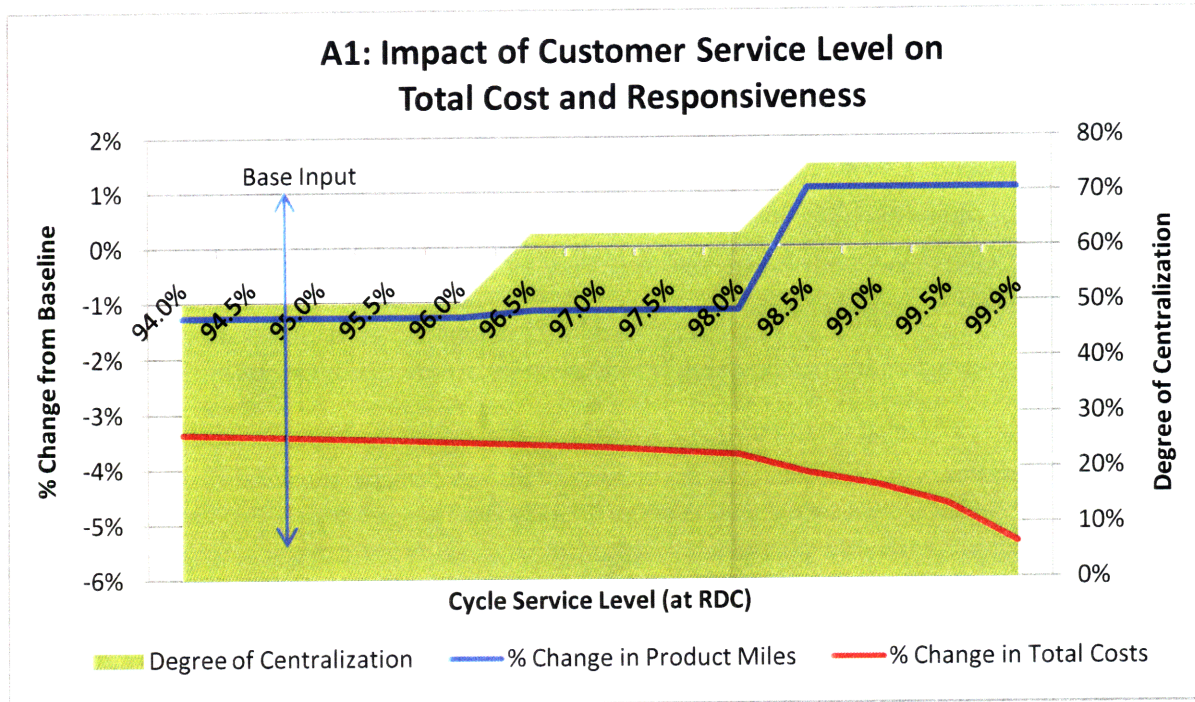


Figure 4.3: Sensitivity analysis for customer service level

Table 4.7: Sensitivity analysis table for customer service level

Scenario	Customer Service Level	Degree of Centralization	Total Cost	Product Miles
Low	94.5%	50%	\$ 251,137	8,944,521
Base Value	98.0%	63%	\$ 258,050	8,955,621
High	99.9%	75%	\$ 271,292	9,155,959

Figure 4.3 and Table 4.7 show that a change in service level from 96% to 98% affects the centralization by increasing it from 50% to 65% with almost no effect on the product miles. We further observe that extremely high service levels in the range of 98% to 100% result in a very high centralization of 75%, but again with a very small increase in the net product miles.

iv) Effect of Supplier to RDC Lead Time on Degree of Centralization

The lead-time from supplier to RDC directly affects the safety stock cost. Higher supplier to district DC lead times would increase the safety stock cost and drive the optimal solution towards centralization. Rail mode typically has higher lead times, in the range of two to three weeks, whereas truck or road mode has smaller lead times, in the range of a few days to a week. Thus different transportation modes can lead to different lead times in a distribution network and different safety stock costs. A sensitivity analysis for lead times helps us evaluate the trade-off between reduced safety-stock due to risk pooling and increased safety stock due to higher lead times.

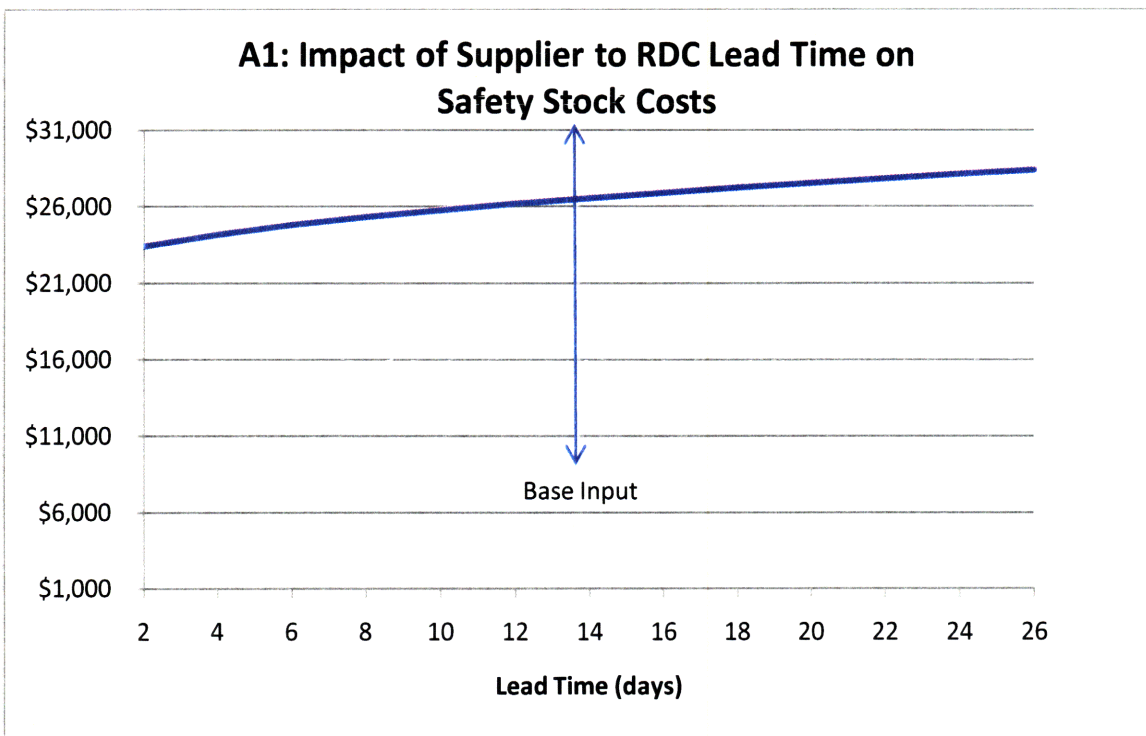


Figure 4.4: Impact of supplier to RDC lead time

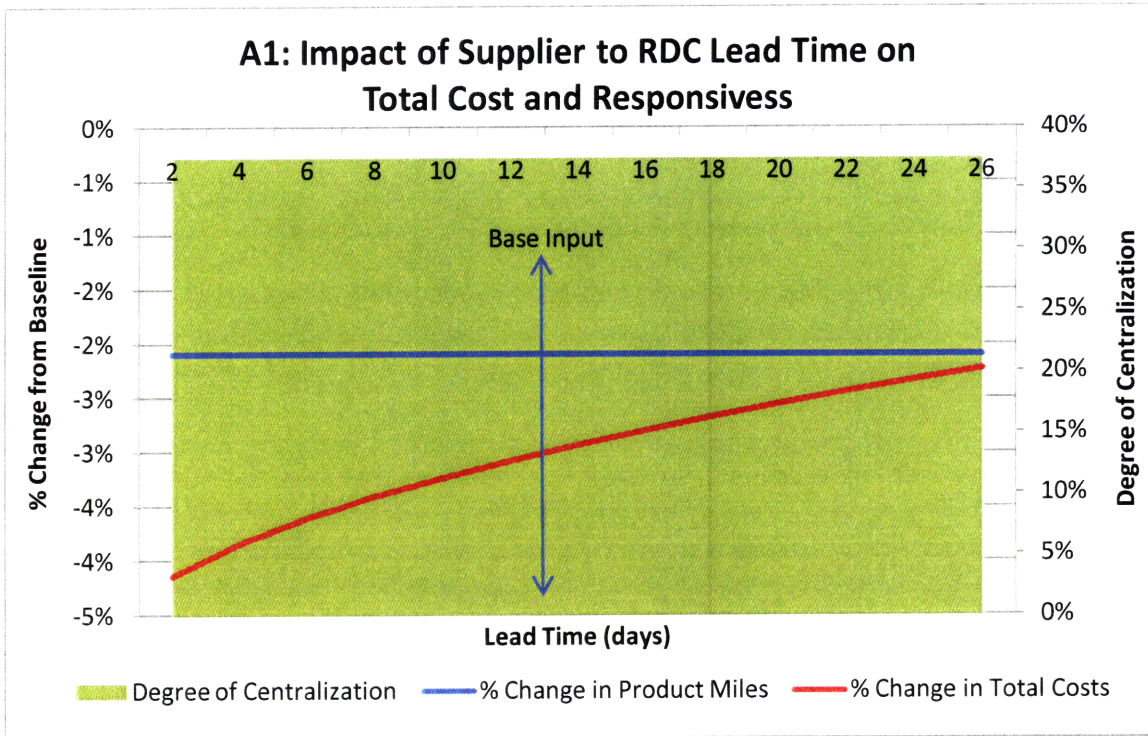


Figure 4.5: Sensitivity analysis for supplier to RDC lead time

Table 4.8: Sensitivity analysis table for supplier to RDC lead time

Scenario	Supplier to RDC Lead Time	Degree of Centralization	Total Cost	Product Miles
Low	4 days	38%	\$ 250,832	8,869,993
Base Value	14 days	38%	\$ 253,197	8,869,993
High	24 days	38%	\$ 254,769	8,869,993

Figure 4.5 and Table 4.8 show that a variation in the lead time does not have any effect on the degree of centralization, which remains at 38%. At the same time the safety stock cost increases, as shown in Figure 4.4. However, the effect of lead time on safety stock cost happens to be much less than the transportation costs for this product. Hence the variation in lead time does not materially change the degree of centralization.

v) **Impact of Demand Variability on Total Costs and Degree of Centralization**

The standard deviation (variability) of daily demand over the whole year affects the safety stock cost. Here we change the standard deviation from -50% to 100% or higher of its base value to see the effect of demand variability on the optimal solution. A higher standard deviation results in an optimal solution that has a higher degree of centralization. This is in line with the “square root law”, which suggests that high demand variability would tend to drive the optimal configuration towards centralization.

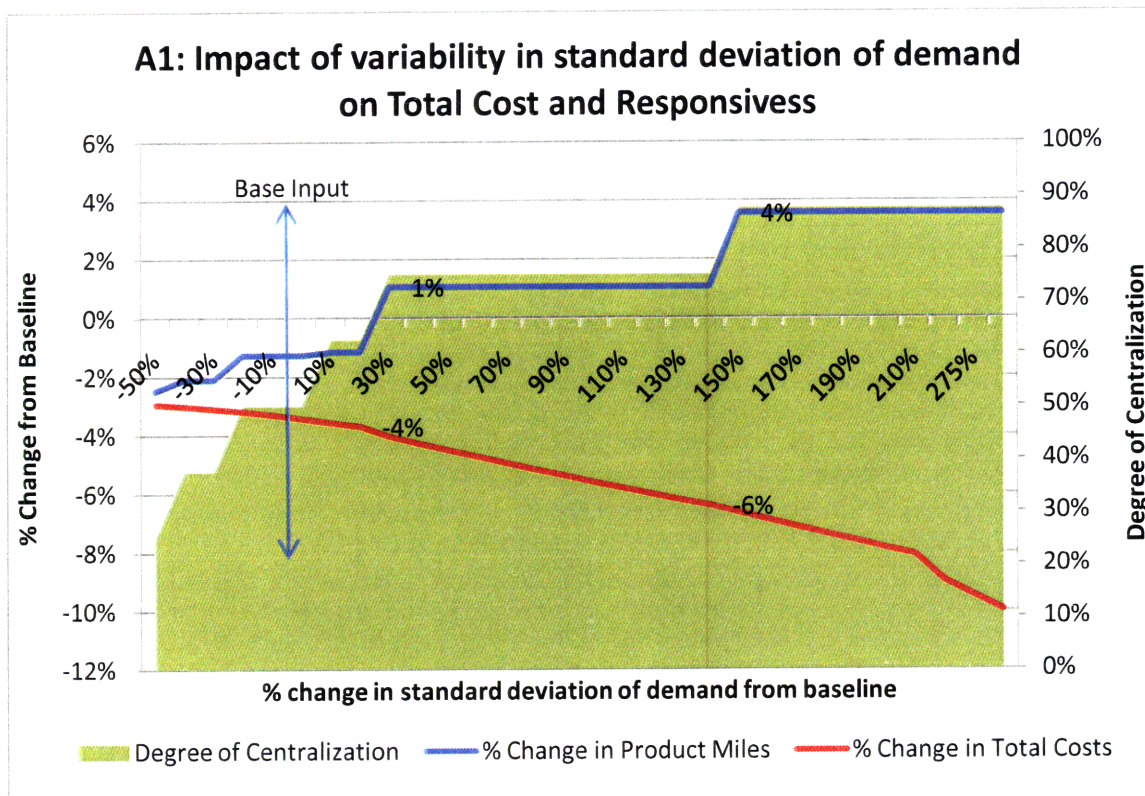


Figure 4.6: Sensitivity analysis for standard deviation of demand

Table 4.9: Sensitivity analysis table for standard deviation of demand

Scenario	Change in Std Deviation	Degree of Centralization	Total Cost	Product Miles
Low	-50%	25%	\$ 238,898	8,835,144
Base Value	0%	50%	\$ 251,847	8,944,521
High	130%	75%	\$ 280,434	9,155,959

The percent change in standard deviation is applied to all the demand points in the base case. Figure 4.6 and Table 4.9 show the effect of the decrease and increase in standard deviation. When the standard deviation goes down by 50% we see that the centralization is at its minimum as there is not much benefit gained by inventory aggregation. As the standard deviation increases by 40% the centralization increases by 15% with a small change in product miles and a total cost savings increase of 0.75%.

vi) Impact of purchase price of product

Here, we analyze the effect of purchase price volatility on the optimal solution. Company A deals with a majority of commodity products that are low priced, but high in volume. The purchase price has a direct impact on the safety stock cost and is thus critical for our study. We vary the purchase price to see the effect of a drop or a hike in the price on the optimal configuration. Higher purchase price increases the degree of centralization and lower price decreases degree of centralization. If the safety stock cost is much less than the cost of transportation, then the effect of the purchase price on the optimal solution would be very small.

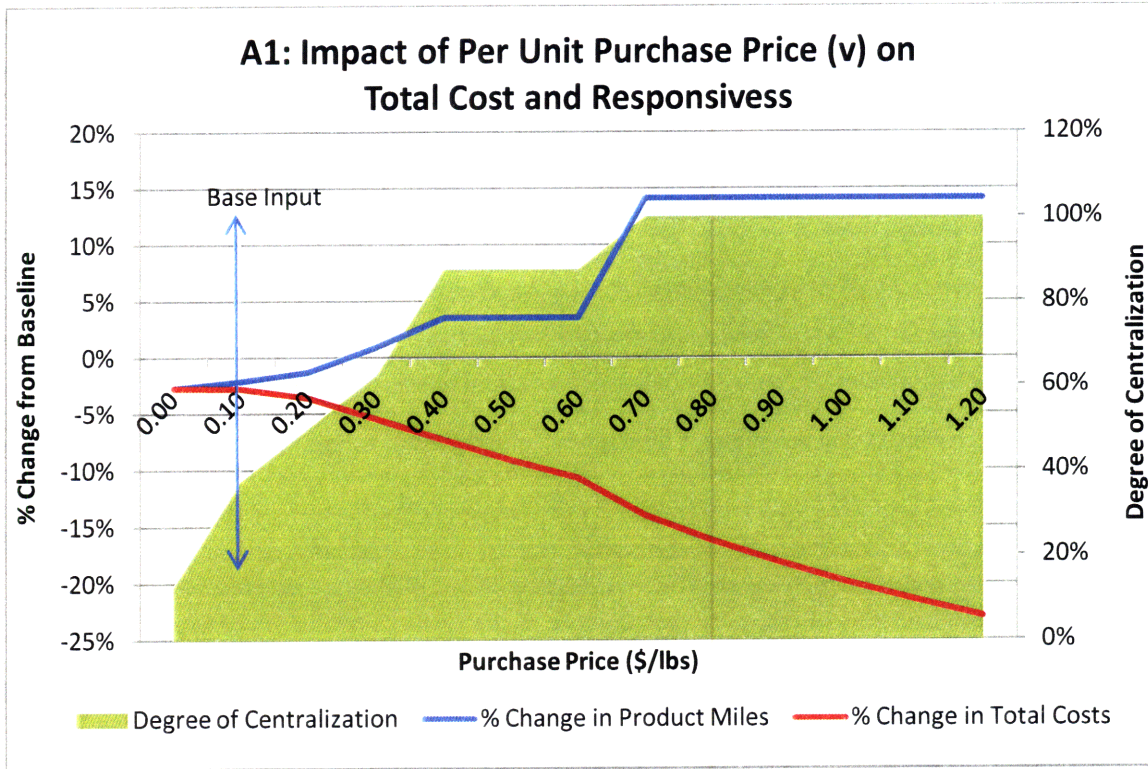


Figure 4.7: Sensitivity analysis for unit purchase price

Table 4.10: Sensitivity analysis table for unit purchase price

Scenario	Unit Purchase Price	Degree of Centralization	Total Cost	Product Miles
Low	0.01 \$/lb	13%	\$ 227,577	8,811,361
Base Value	0.12 \$/lb	38%	\$ 253,197	8,869,993
High	0.40 \$/lb	88%	\$ 305,157	9,383,147

In Figure 4.7 we see that as the price increases, degree of centralization increases due to the benefit of pooling inventory. A key insight from Figure 4.7 is that an increase in purchase price beyond \$0.70 has no impact on the product miles (0% change) but reduces safety stock cost relative to the new optimal solution for the higher purchase price.

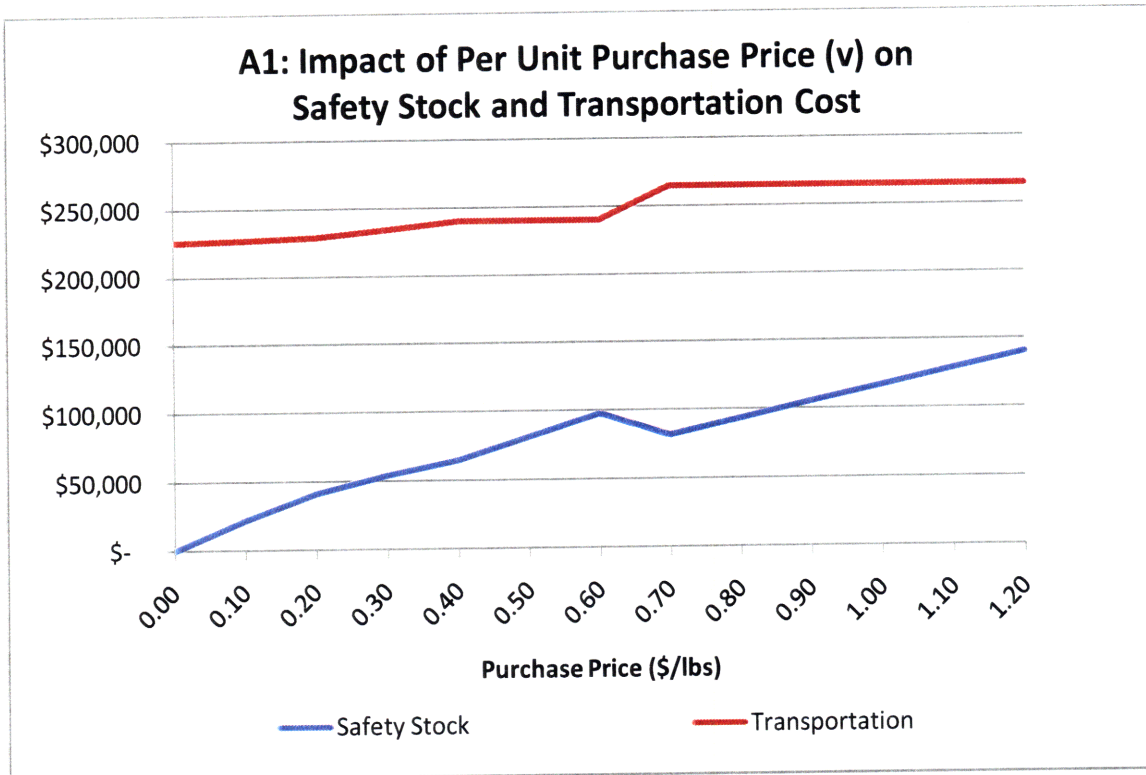


Figure 4.8: Impact of unit purchase price

4.2 Generalization of Quantitative Results to Remaining Products

In this section we extend the results obtained through our quantitative analysis to a larger set of products across seven product families: A, B, C, D, E, F, and G spanning both specialty and commodity products. We observed common patterns across these product families in terms of standard deviation of demand, annual volume, unit purchase price, and the physical location of suppliers and DCs. The sensitivity analysis performed on a representative set of products shows that these inputs play a critical role in the decision of centralization. Hence we use these inputs to generalize our quantitative results across products having similar attributes. This helps in developing a solution that is applicable across a diverse set of product families and a large number of products.

Certain product properties can influence decisions in a non-numeric way. For example, hazardous materials are difficult to store at a large number of locations in a decentralized system due to complicated handling requirements. It is advantageous to centralize such products to reduce the costs involved in training and special handling.

Although a complete quantitative analysis of every product would provide the most optimal results, such analysis can be very time consuming. A generalization of the results based on product attributes can help make quick decisions, when faced with tight constraints on time and resources. In Table 4.11 below we present the qualitative, generalized results for all products in the geographical region under consideration. The mark “C” denotes centralization and “D” denotes decentralization for each product. The products in bold are those for which detailed quantitative results are presented in Appendix A.

In order to make the decision of “C” versus “D”, we compared the different attributes of each product within a family with the attributes of a product for which quantitative analysis has been performed (shown in bold). If a product has similar attributes as those which are in bold, then we extend our result directly from our quantitative analysis. If certain attributes are very different, then we use the sensitivity analysis of those attributes to decide whether the solution should be centralized or decentralized.

Table 4.11: Generalization of quantitative results to other products

Product Code	Product Type	Total Annual Demand (lbs)	Average Demand (lbs)	Std Dev of Demand (lbs)	Coeff of Variation	Unit Cost (\$/lbs)	Fast/Slow (Annual Repln)	Number of Vendors	Decision
A1	Commodity	16,313,555	1,631,356	2,177,648	1.33	\$ 0.07	66	1	C
A2	Commodity	199,271,419	13,284,761	8,628,802	0.65	\$ 0.06	203	2	C
A3	Commodity	90,002,818	10,000,313	7,231,283	0.72	\$ 0.05	120	5	C
A4	Commodity	26,679,926	6,669,982	2,416,479	0.36	\$ 0.06	58	2	C
B1	Specialty	626,329	78,291	54,145	0.69	\$ 0.08	46	3	C
B2	Specialty	3,853,732	3,853,732	0	0.00	\$ 0.01	12	1	D
B3	Specialty	137,898	68,949	51,052	0.74	\$ 0.44	10	2	C
C1	Specialty	19,547,852	1,954,785	2,265,824	1.16	\$ 0.03	111	3	C
D1	Commodity	4,332,844	618,978	1,309,034	2.11	\$ 0.03	20	4	D
D2	Commodity	300,380	150,190	209,997	1.40	\$ 0.06	5	2	D
D3	Commodity	23,668,605	3,381,229	5,995,252	1.77	\$ 0.05	25	3	C
D4	Commodity	45,546,512	7,591,085	11,461,847	1.51	\$ 0.04	23	2	D
D5	Commodity	211,584,035	16,275,695	48,725,767	2.99	\$ 0.02	95	8	C
E1	Specialty	2,909,490	969,830	365,703	0.38	\$ 0.26	24	1	C
E2	Specialty	11,256,040	1,876,007	2,876,425	1.53	\$ 0.26	28	2	C
E3	Specialty	13,000	13,000	0	0.00	\$ 0.29	1	1	D
E4	Specialty	3,218,535	643,707	788,272	1.22	\$ 0.20	18	2	C
E5	Specialty	444,942	222,471	203,942	0.92	\$ 0.23	3	1	D
E6	Specialty	10,264,540	2,052,908	3,360,906	1.64	\$ 0.24	24	1	C
E7	Specialty	57,000	57,000	0	0.00	\$ 0.24	1	1	D
F1	Commodity	4,767,938	1,589,313	1,931,901	1.22	\$ 0.57	14	1	D
F2	Commodity	2,929,810	1,464,905	1,817,130	1.24	\$ 0.57	13	1	D
F3	Commodity	8,192,184	2,730,728	4,041,601	1.48	\$ 0.54	18	1	D
F4	Commodity	2,271,000	567,750	651,536	1.15	\$ 0.46	21	1	D
F5	Commodity	5,794,787	1,448,697	2,752,890	1.90	\$ 0.48	19	1	D
G1	Specialty	6,070,156	1,214,031	1,125,796	0.93	\$ 0.30	23	2	D
G2	Specialty	1,184,540	592,270	763,972	1.29	\$ 0.32	7	1	D
G3	Specialty	1,029,540	343,180	127,048	0.37	\$ 0.27	5	1	D
G4	Specialty	286,500	143,250	80,851	0.56	\$ 0.34	2	1	D

5 Conclusions

We used our analytical model to determine the optimal positioning of inventory in our sponsor company's multi-echelon distribution network. Initially we focused on gathering data and organizational information. A review of the inventory centralization literature shaped our understanding of multi-echelon inventory theory and the analytical approaches used in this field. We then used this understanding to develop our model. In this chapter we present our conclusions and four key insights, drawn from the development and use of our model. We conclude by providing three broadly applicable recommendations for the efficient management of inventory in a multi-echelon distribution network. We also outline future research to extend our model further.

5.1 Key Insights

Many of the important results have already been described in Chapter 4. Here we summarize four key insights.

- i) **Transportation Costs:** Our model shows that centralization increases the total miles travelled by the product from supplier to end customer, which tends to *increase* transportation cost. However, centralization also presents opportunities for lane consolidation, which *decreases* inbound transportation costs. Thus, the net effect of centralization on transportation costs is highly dependent on the degree of lane consolidation that can be achieved for any given product.

- ii) **Inventory Costs:** We observe that the safety stock holding cost reduces as we achieve higher degree of centralization in the company's distribution network. This is a result of pooling the risk due to demand uncertainty from various district DCs. However, the results also show that for a distribution network serving large quantities of bulk items, the cost of transportation often dominates the cost of holding inventory. Therefore the optimal solution can often appear counter-intuitive.

- iii) **Service Levels:** The desired service level is an important input to the safety stock cost. Since safety stock costs for bulk products are typically small compared to transportation costs, it is possible to have large gains in service levels with a relatively small impact on total costs. The cost-versus-service tradeoff for bulk products is clearly demonstrated by our optimization model.

- iv) **Responsiveness:** Our model shows that inventory centralization reduces supply chain responsiveness due to the increase in distance travelled. However, for products having low transportation and high inventory costs, centralization can reduce total costs, with a minimal impact on responsiveness. This is particularly true for products served by vendors in close geographic proximity to the RDC.

5.2 Managerial Recommendations

Based on the insights presented above, we offer the following three managerial recommendations.

- i) **Lane consolidation:** For high volume bulk products, centralization can reduce total costs by up to 30% with lane consolidation. The supplier-district DC lane is usually served by truck. It is possible to achieve high degree of consolidation by using rail shipments instead of shipping by truck. Hence we recommend centralizing such products to an RDC that has rail access.

- ii) **Identification of quick-wins:** Some of the low volume specialty products have suppliers who are geographically close to the RDC. We recommend a quick identification of such products in the distribution network. These are the low-hanging fruit because centralization can deliver immediate reduction in total costs (5% to 10%), with almost no impact on responsiveness and the existing transportation network.

- iii) **Transportation procurement:** Inventory positioning strategy can play a big role in defining the company's transportation procurement strategy. As more centralization of inventory is achieved, transportation between the RDC and district DCs becomes critical for maintaining high customer service levels. Centralization may also result in higher lane capacities on the supplier to RDC leg. We recommend using the greater leverage that higher capacity provides to negotiate more favorable contracts with vendors and transportation providers.

We conclude by commenting on the importance of constructing data-driven, analytical models to determine an optimal solution for such problems. Our research has shown that

the true optimal solution can often be counter-intuitive, primarily because of the multiple tradeoffs involved in making such decisions. A good analytical model that is able to quantify these tradeoffs will enable managers to make accurate decisions.

5.3 Future Research

Several extensions to our work are possible by relaxing the assumptions in our model and conducting further research on lane consolidation and the effect of supply variability. Our model assumes demand at all facilities to be normally distributed and independent of each other. Incorporating the effect of different demand distributions and correlation in demand patterns would make the model more robust. It is also possible to extend the model to take into consideration capacity restrictions on supplier, district and central facilities. Further research could also consider the effect of variability in supplier lead times. A more granular study of the transportation network would also add to the accuracy of the model by identifying transportation costs and consolidation opportunities on each lane, instead of generalizing to three transportation legs. As we have demonstrated, quantitative analysis of this system can provide significant costs savings, and exploring any of these research extensions could extend that value further.

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Appendix A: Results for a Representative Set of Products

In Chapter 4 we described the model outputs and an interpretation of the optimization and baseline scenarios. We also explained the various sensitivity analyses that were performed to test the variation in the optimal solution with a change in the input parameters.

In this appendix we show the results we obtained by running our model for a representative set of products. We demonstrate the sensitivity analysis of different inputs against input parameters such as lane consolidation, transportation multiplier, unit purchase price, lead time from supplier to RDC and change in standard deviation of demand. A snapshot of the sensitivity analysis is also shown in tabular format for low, high and baseline values of the input variables.

The set of products we have chosen for detailed quantitative analysis are: B1, C1, A2, D4, D5, E1, and F1. These products represent all seven product families considered in this thesis. The product characteristics for each product are shown in Table 4.11 of Chapter 4. That table also shows characteristics of other products within these families.

A.1 Quantitative Results for Product B1

Optimization Run Results

No	Description	Units	Centralized	De-Centralized
1	Total Number of District Plants Centralized	#	5	3
2	Aggregate Safety Stock Cost	\$/year	\$ 867	\$ 1,031
3	Aggregate Transportation Cost	\$/year	\$ 26,182	\$ 14,506
4	Total Product Miles Traveled	lbs-miles		1,611,361

Baseline Cost Comparison

No	Description	Units	Baseline	Optimized	% change
1	Aggregate Safety Stock Cost	\$/year	\$ 2,603	\$ 1,898	-27%
2	Aggregate Transportation Cost	\$/year	\$ 42,819	\$ 40,687	-5%
3	Product Miles	lbs-miles	1,517,633	1,611,361	6%

Figure A. 1: Quantitative results for product B1

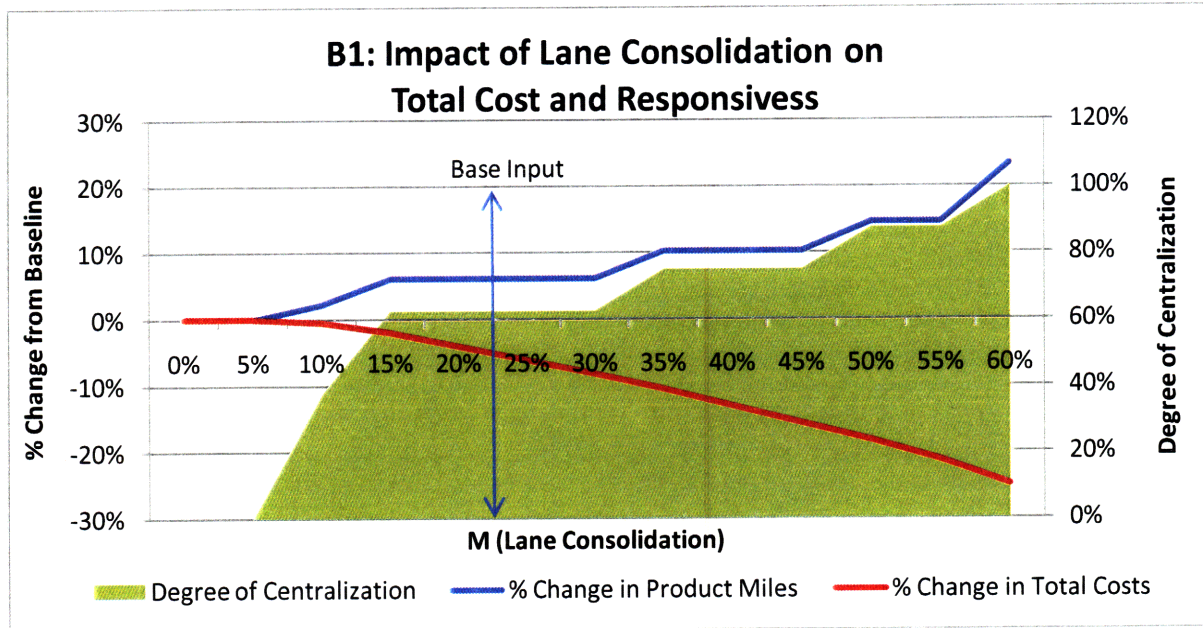


Figure A. 2: Sensitivity analysis for product B1

Table A. 1: Sensitivity table for product B1

Scenario	Lane Consolidation	Degree of Centralization	Total Cost	Product Miles
Low	5%	0%	\$45,422	1,517,633
Base Value	25%	63%	\$42,632	1,611,361
High	50%	88%	\$37,102	1,739,503

A.2 Quantitative Results for Product C1

Optimization Run Results

No	Description	Units	Centralized	De-Centralized
1	Total Number of District Plants Centralized	#	6	4
2	Aggregate Safety Stock Cost	\$/year	\$ 1,626	\$ 4,560
3	Aggregate Transportation Cost	\$/year	\$ 173,829	\$ 165,402
4	Total Product Miles Traveled	lbs-miles		15,287,578

Baseline Cost Comparison

No	Description	Units	Baseline	Optimized	% change
1	Aggregate Safety Stock Cost	\$/year	\$ 8,401	\$ 6,186	-26%
2	Aggregate Transportation Cost	\$/year	\$ 354,903	\$ 339,231	-4%
3	Product Miles	lbs-miles	15,192,758	15,287,578	1%

Figure A. 3: Quantitative results for product C1

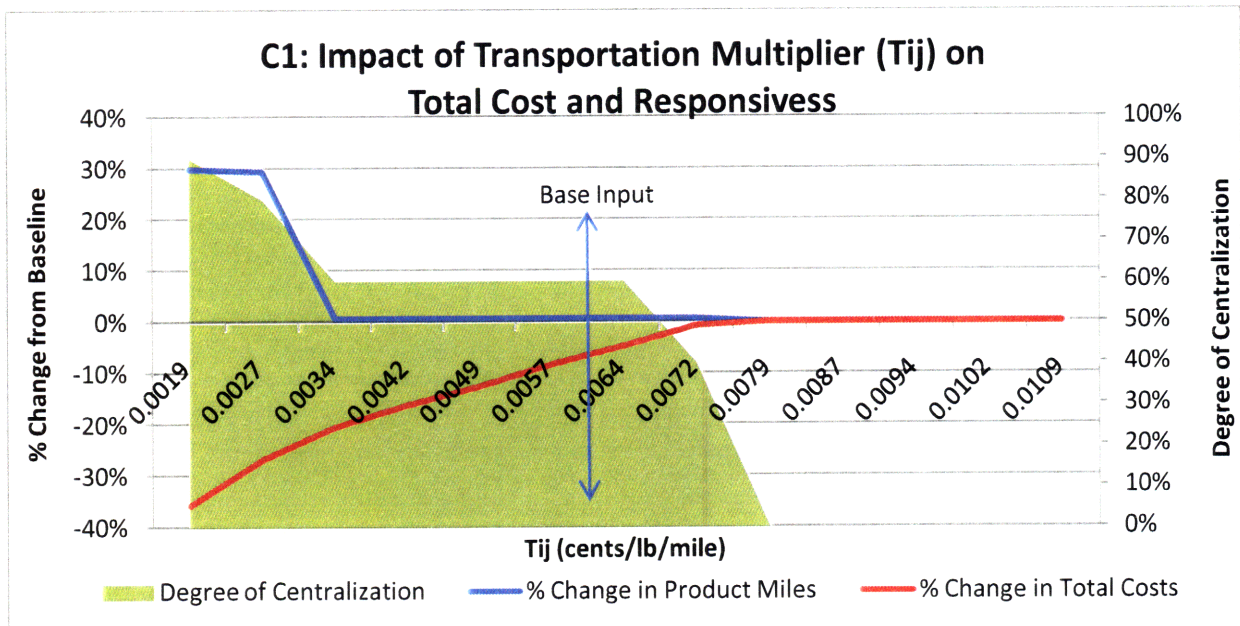


Figure A. 4: Sensitivity analysis for product C1

Table A. 2: Sensitivity table for product C1

Scenario	Transportation Multiplier	Degree of Centralization	Total Cost	Product Miles
Low	0.0027	80%	\$263,470	19,667,729
Base Value	0.0064	60%	\$342,524	15,287,578
High	0.0102	0%	\$359,375	15,192,758

A.3 Quantitative Results for Product A2

Optimization Run Results

No	Description	Units	Centralized	De-Centralized
1	Total Number of District Plants Ce	#	4	9
2	Aggregate Safety Stock Cost	\$/year	\$ 9,023	\$ 41,373
3	Aggregate Transportation Cost	\$/year	\$ 1,051,492	\$ 2,142,978
4	Total Product Miles Traveled	lbs-miles		187,843,279

Baseline Cost Comparison

No	Description	Units	Baseline	Optimized	% change
1	Aggregate Safety Stock Cost	\$/year	\$ 56,145	\$ 50,396	-10%
2	Aggregate Transportation Cost	\$/year	\$ 3,538,947	\$ 3,194,470	-10%
3	Product Miles	lbs-miles	197,872,336	187,843,279	-5%

Figure A. 5: Quantitative results for product A2

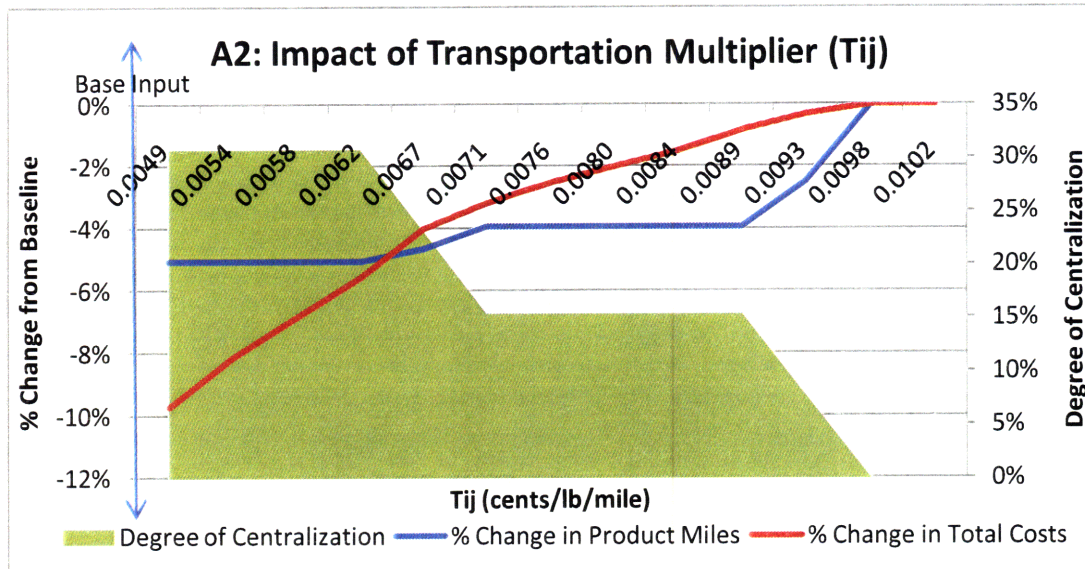


Figure A. 6: Sensitivity analysis for product A2

Table A. 3: Sensitivity table for product A2

Scenario	Transportation Multiplier	Degree of Centralization	Total Cost	Product Miles
Low	0.0049	31%	\$3,212,469	187,843,279
Base Value	0.0049	31%	\$3,212,469	187,843,279
High	0.0098	0%	\$3,558,998	197,872,336

A.4 Quantitative Results for Product D4

No	Description	Units	Centralized	De-Centralized
1	Total Number of District Plants Ce	#	1	5
2	Aggregate Safety Stock Cost	\$/year	\$ 1	\$ 48,067
3	Aggregate Transportation Cost	\$/year	\$ 31,379	\$ 1,795,795
4	Total Product Miles Traveled	lbs-miles		42,590,161

Baseline Cost Comparison

No	Description	Units	Baseline	Optimized	% change
1	Aggregate Safety Stock Cost	\$/year	48,068.00	\$ 48,068.16	0.00%
2	Aggregate Transportation Cost	\$/year	1,828,126.31	\$ 1,827,174.38	-0.05%
3	Product Miles	lbs-miles	42,527,985.67	\$ 42,590,161.34	0.15%

Figure A. 7: Quantitative results for product D4

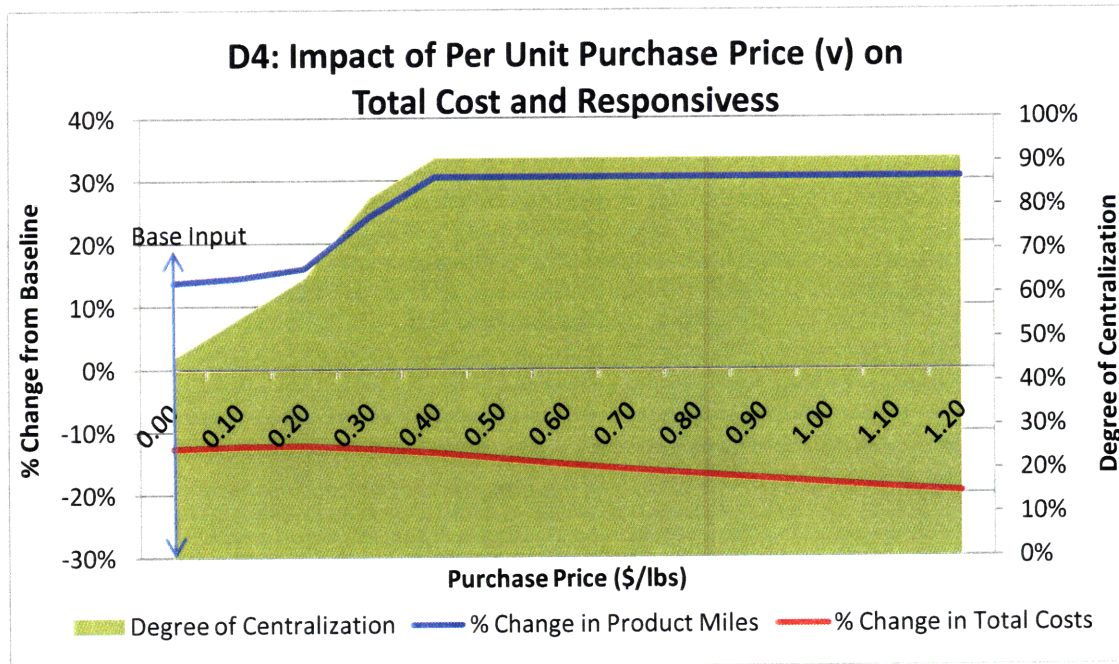


Figure A. 8: Sensitivity analysis for product D4

Table A. 4: Sensitivity table for product D4

Scenario	Unit Purchase Price	Degree of Centralization	Total Cost	Product Miles
Low	0.001	45%	\$2,048,749	61,947,081
Base Value	0.040	17%	\$1,875,243	42,590,161
High	0.900	91%	\$2,490,145	71,062,157

A.5 Quantitative Results for Product D5

Optimization Run Results

No	Description	Units	Centralized	De-Centralized
1	Total Number of District Plants Ce	#	5	6
2	Aggregate Safety Stock Cost	\$/year	\$ 14,644	\$ 22,540
3	Aggregate Transportation Cost	\$/year	\$ 1,692,874	\$ 550,899
4	Total Product Miles Traveled	lbs-miles		61,947,081

Baseline Cost Comparison

No	Description	Units	Baseline	Optimized	% change
1	Aggregate Safety Stock Cost	\$/year	\$ 37,676	\$ 37,184	-1%
2	Aggregate Transportation Cost	\$/year	\$ 2,344,274	\$ 2,243,773	-4%
3	Product Miles	lbs-miles	54,429,405	61,947,081	14%

Figure A. 9: Quantitative results for product D5

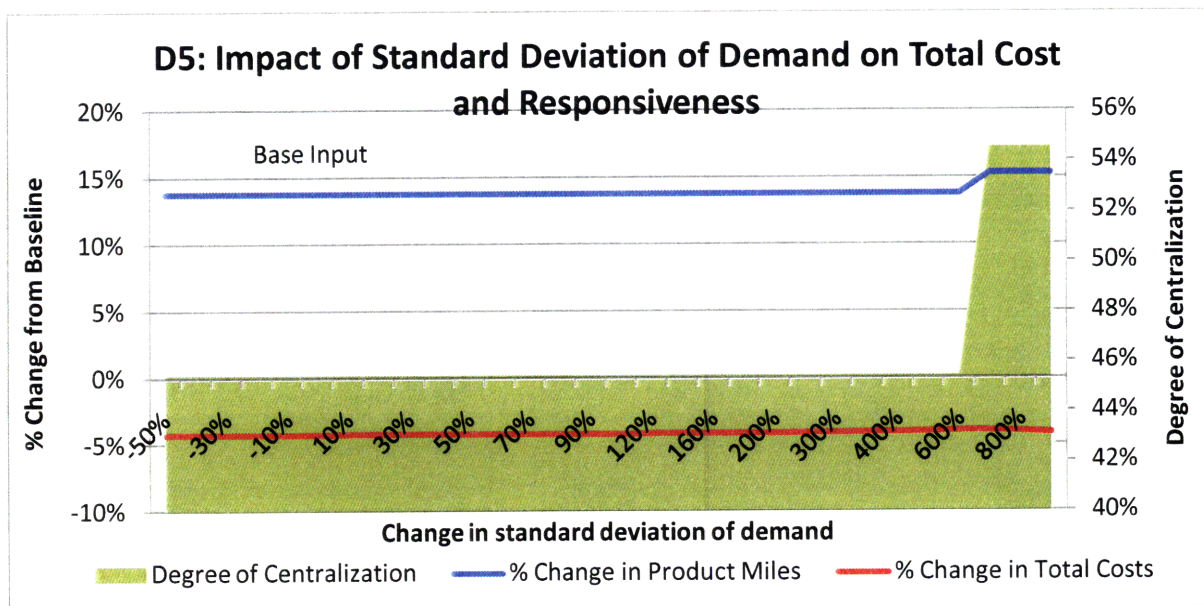


Figure A. 10: Sensitivity analysis for product D5

Table A. 5: Sensitivity table for product D5

Scenario	Change in Std Deviation	Degree of Centralization	Total Cost	Product Miles
Low	-50%	45%	\$2,262,365	61,947,081
Base Value	0%	45%	\$2,280,957	61,947,081
High	200%	45%	\$2,355,325	61,947,081

A.6 Quantitative Results for Product E1

Optimization Run Results

No	Description	Units	Centralized	De-Centralized
1	Total Number of District Plants Ce	#	3	4
2	Aggregate Safety Stock Cost	\$/year	\$ 12,582	\$ 60,834
3	Aggregate Transportation Cost	\$/year	\$ 785,629	\$ 876,679
4	Total Product Miles Traveled	lbs-miles		36,888,815

Baseline Cost Comparison

No	Description	Units	Baseline	Optimized	% change
1	Aggregate Safety Stock Cost	\$/year	\$ 76,681	\$ 73,416	-4%
2	Aggregate Transportation Cost	\$/year	\$ 1,770,606	\$ 1,662,308	-6%
3	Product Miles	lbs-miles	36,201,303	36,888,815	2%

Figure A. 11: Quantitative results for product E1

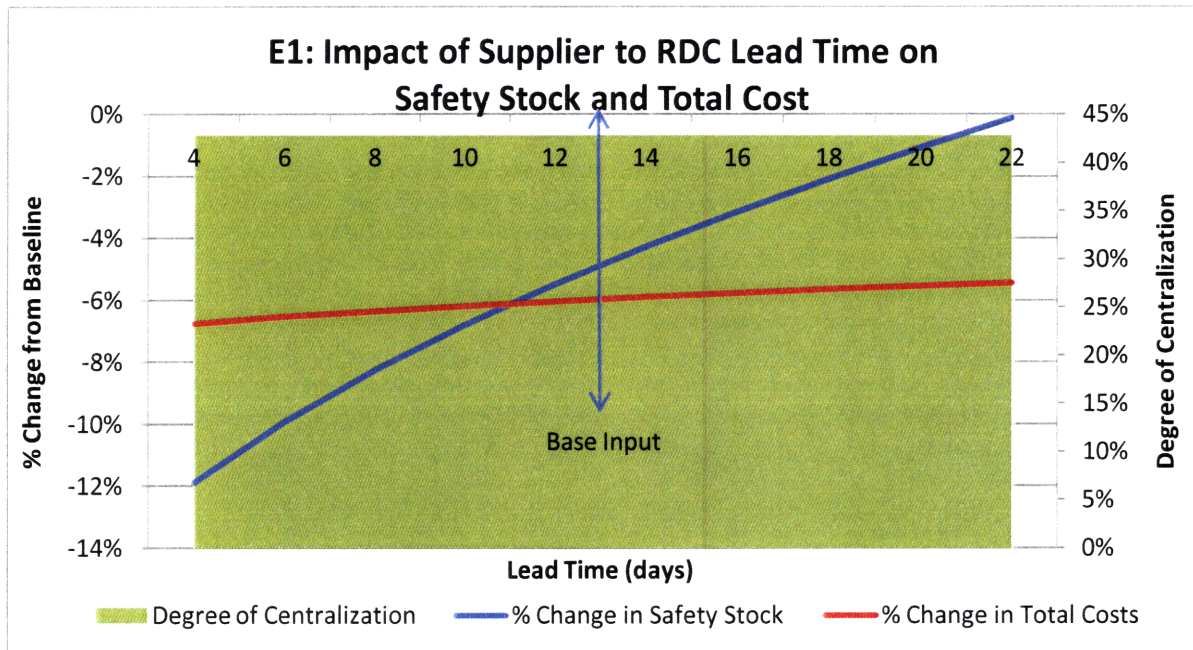


Figure A. 12: Sensitivity analysis for product E1

Table A. 6: Sensitivity table for product E1

Scenario	Supplier to RDC Lead Time	Degree of Centralization	Total Cost	Product Miles
Low	6 days	43%	\$1,867,082	36,888,815
Base Value	14 days	43%	\$1,879,964	36,888,815
High	22 days	43%	\$1,889,423	36,888,815

A.7 Quantitative Results for Product F1

Optimization Run Results

No	Description	Units	Centralized	De-Centralized
1	Total Number of District Plants Centralized	#	0	3
2	Aggregate Safety Stock Cost	\$/year	\$ -	\$ 62,344
3	Aggregate Transportation Cost	\$/year	\$ -	\$ 408,708
4	Total Product Miles Traveled	lbs-miles	9,909,278	

Baseline Cost Comparison

No	Description	Units	Baseline	Optimized	% change
1	Aggregate Safety Stock Cost	\$/year	\$ 62,344	\$ 62,344	0.000%
2	Aggregate Transportation Cost	\$/year	\$ 408,708	\$ 408,708	0.000%
3	Product Miles	lbs-miles	9,909,278	9,909,278	0.000%

Figure A. 13: Quantitative results for product F1

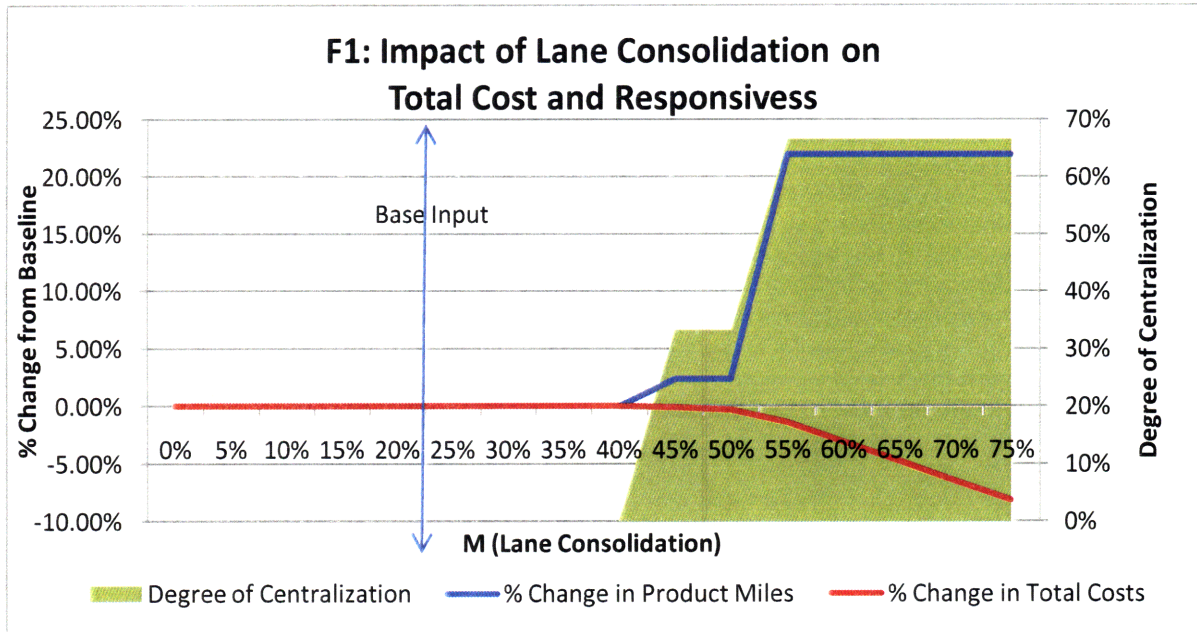


Figure A. 14: Sensitivity analysis for product F1

Table A. 7: Sensitivity table for product F1

Scenario	Lane Consolidation	Degree of Centralization	Total Cost	Product Miles
Low	5%	0%	\$470,829	9,909,278
Base Value	25%	0%	\$470,829	9,909,278
High	50%	33%	\$469,168	10,140,430

Appendix B: Optimization Model User Guide

This section explains how to use the optimization model that has been described in our thesis. The optimization model was implemented in Microsoft Excel © 2007 with the LINDO 9.0 Non Linear Solver Add-In available from www.lindo.com. We recommend having the excel file open while reading through this user guide. We divide the appendix broadly into the following sections:

- B.1 Introduction to Optimization Model
 - B.2 Setting Up the Model
 - B.2.1 Input Parameters Setup
 - B.2.2 Input Facilities/Demand Setup
 - B.2.3 Input Distances/Lane Data Setup
 - B.3 Running the Model
 - B.3.1 NLP Formulation
 - B.3.2 Results
 - B.4 Sensitivity Testing Setup
-

B.1 Introduction to Optimization Model

The optimization model can be setup and run for one product at a time. The tool optimizes the given network of facilities of suppliers, district DCs and central DCs and given demand data to position inventory by minimizing the total cost comprising of transportation and safety stock holding costs at the facilities. For each run and a given set of input parameters, the model generates a set of results. The results include the various costs discussed in Chapter 3 and their comparison with the baseline values. The results

also give an exact assignment of the district DC to the central RDC. The spreadsheet is organized into separate tabs. Each tab is discussed in detail in the following sections: setting up the model, running the model and sensitivity testing.

B.2 Setting Up the Model

B.2.1 Input Parameters Setup (Excel Tab: Input Parameters)

Figure B.1 gives a snapshot of the input parameters setup tab. The cells in yellow are input through the sensitivity tab. All the remaining cells (in gray) accept values through this tab. The explanation for each parameter is provided alongside the parameter name.

VARIABLES	Description	Units	Value
Vcentral	purchase cost per unit of item at RDC (possible discounts from supplier due to consolidation)	\$/lbs	0.56
r	Holding cost	\$/\$/year	0.35
Lcentral	Lead time (average between Supplier and RDC)	days	10
CSLcentral	Service Level desired (outbound from RDC or Central DC to the District Plants)	%	95.0%
Ndays	Number of days in a year when the products are used	days/year	365
M	% Reduction in transportation costs per unit volume of consolidation at a RDC	%	25%
Tki	Transportation Multiplier (k->i : supplier to RDC)	\$/lbs/mile	0.000113
Tij	Transportation Multiplier (i->j: RDC to DC)	\$/lbs/mile	0.000113
Tkj	Transportation Multiplier (k->j: supplier to DC)	\$/lbs/mile	0.000113

Figure B. 1: Input parameters

B.2.2 Input Facilities/Demand Setup (Excel Tabs: Input Facilities, Input Demand)

Figure B.2 gives a snapshot of the Input facilities tab. The facility IDs for the district DCs, central DCs and suppliers can be entered only here. They are then automatically populated in all the remaining tabs. The user must also enter the total number of facilities in the lower portion.

Facilities List	
Key	Description
DC	District DC (De-centralized Facility)
RDC	Regional Distribution Center (Central Facility)
SUP	Supplier to RDC and/or DC

District DCs		Regional DCs (RDC)		Suppliers	
Facility Name	Facility Number	Facility Name	Facility Number	Facility Name	Facility Number
	2049		2052		3010438
	2061				
	2064				
Total	3	Total	1	Total	1

Figure B. 2: Input facilities

Figure B.3 shows the Input demand tab. The standard deviation of demand and mean daily demand must be entered on this tab only. The standard deviation should only be entered in the lowest row. Also, when removing facilities, the standard deviation and mean demand for the particular facility must be set to zero in this tab.

Input - Facilities (District Plants)- Demand Data Inputs			
	2049	2061	2064
Average Demand (U) (lb/day)	3605	21184	3502
Variance of Demand (VARj)	80240083	1678605905	125965450
Standard Deviation (SIGMAj) (lb/day)	8958	40971	11223
Input std dev data to be used as input above			
Standard Deviation (SIGMAj) (lb/day)	8958	40971	11223

Figure B. 3: Input demand

B.2.3 Input Distances and Lane Data Setup (Excel Tabs: Input Distances, Input Lane)

Figure B.4 shows the Input Distances tab. The distances (in miles) between the various facilities must be populated in this matrix. Again, when removing facilities, the distances for the corresponding entry in this table must be set to zero.

d(kj)			Supplier to District DC Distances - d(kj)										Units		miles			
			District Plants															
Suppliers	2049	2061	2064	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
3010438	59	384	446	0	0	0	0	0	0	0	0	0	0	0	0	0	0	

Figure B. 4: Input distances

Figure B.5 shows the Input Lane setup. Each entry in the matrix here represents the lane carrying capacity in lbs. The lane capacities are used only to compute an estimate of the Lane Consolidation Factor (M). This estimate is provided only for the user’s guidance. The user may input a different value for M in the input parameters tab.

Lane Capacities - Supplier to District Plants (lbs)			District Plants													
Suppliers	2049	2061	2064	0	0	0	0	0	0	0	0	0	0	0	0	0
3010438	200000	200000	200000													

Figure B. 5: Input lane capacities

B.3 Running the Model

The model can be only run through the “Add Ins” tab on the Microsoft excel 2007 menu options. Once the solver is set to run with the “Global Option”, the user has to hit the “Solve” button and the output is produced in the tabs Results and NLP Formulation. These are described in the following two sections.

B.3.1 NLP Formulation (Excel tab: NLP Formulation)

Figure B.6 shows the NLP Formulation table where the topmost section on decision-variables is auto populated by the solver after a run is completed. The 0 represents decentralization for the district DC on the columns and the 1 shows the centralization of a district DC at a particular RDC (shown on the rows).

Decision Variables Xij's		District Plants				
	2049	2061	2064	0	0	0
RDCs	2052	0	0	0	0	0
	0	0	0	0	0	0
	0	0	0	0	0	0
	0	0	0	0	0	0
	0	0	0	0	0	0
	0	0	0	0	0	0
	0	0	0	0	0	0
	0	0	0	0	0	0
	0	0	0	0	0	0
	0	0	0	0	0	0

Figure B. 6: NLP formulation - decision variables

Figure B.7 shows the snapshot of objective function components. The remaining part of the tab contains the constraints.

Objective Function		\$	471,052
Objective Function Cost Components (annual costs) (\$/year)			
Cost Comp Description	Centralized	De-Centralized	
Aggregate Ordering Cost (incorporating CSL)	\$ -	\$ 62,344	
Aggregate Cycle Stock Cost			
Aggregate Transportation Cost (RDC to DC Plant) (ij)	\$ -		
Aggregate Transportation (Supplier to Central Location) (ki)		\$ -	
Aggregate Transportation (Supplier to De-Centralized Location) (kj)		\$ 408,708	

Figure B. 7: NLP formulation - objective function components

B.3.2 Results (Excel Tab: Results)

Figure B.8 shows a snapshot of the results tab. The user can refer to just this tab to see the centralized DCs, cost breakups, and baseline scenario comparison for any run.

Optimization Run Results

No	Description	Units	Centralized	De-Centralized
1	Total Number of District Plants Centralized	#	0	3
2	Aggregate Safety Stock Cost	\$/year	\$ -	\$ 62,344
3	Aggregate Transportation Cost	\$/year	\$ -	\$ 408,708
4	Total Product Miles Traveled	lbs-miles	9,909,278	

Baseline Cost Comparison

No	Description	Units	Baseline	Optimized	% change
1	Aggregate Safety Stock Cost	\$/year	\$ 62,344	\$ 62,344	0.000%
2	Aggregate Transportation Cost	\$/year	\$ 408,708	\$ 408,708	0.000%
3	Product Miles	lbs-miles	9,909,278	9,909,278	0.000%

Summary - District to RDC Assignment

RDC's	Proposed Centralization - Districts to RDC Assignment
2032	
0	

Figure B. 8: Results

B.4 Sensitivity Testing Setup

The model has a built-in sensitivity analysis for six of the input parameters. These parameters are listed in the table below along with the corresponding excel tab names.

Table B. 1: Excel tabs for sensitivity analysis

Input Parameter for Sensitivity Analysis	Excel Tab Name
Lane Consolidation Factor	Sensitivity - M
Transportation Multiplier	Sensitivity - Tij
Lead Time	Sensitivity - L
Purchase Price	Sensitivity - v
Customer Service Level	Sensitivity - CSL
Standard Deviation	Sensitivity - stddev

Figure B.9 shows the setup of the sensitivity tab. The area in gray is the set of outputs generated by the model for each value of the input variable. The sensitivity table is also shown in the form of a graph.

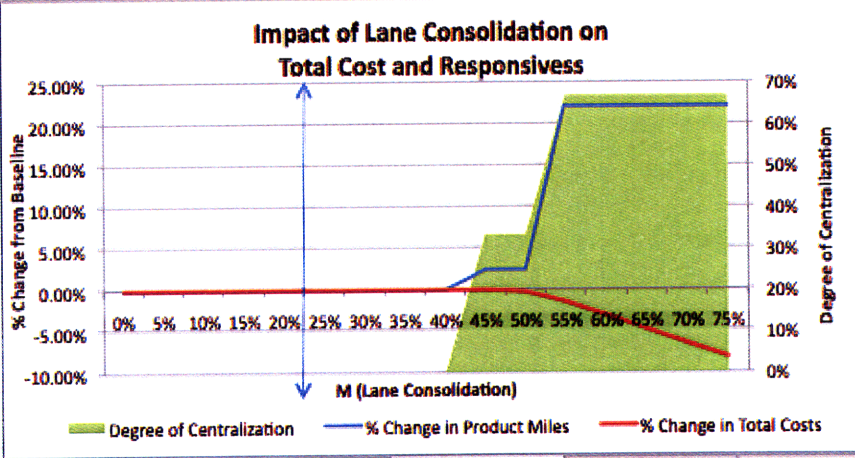
Figure B. 9: Excel screenshot for sensitivity - M (Lane Consolidation Factor)

Input M	Distribution Network Configuration				Safety Stock Cost		Aggregate Costs			
M	No of DC's Centralized	Degree of Centralization	Product Miles	% Change in Product Miles	Centralized	Decentralized	Safety Stock	% Change in Safety Stock	Transportation	% Change in Transportation
25%	0	0%	9,909,278	0.00%	-	62,344	\$ 62,344	0.00%	\$ 408,708	0.00%
30%	0	0%	9,909,278	0.00%	-	62,121	\$ 62,121	0.00%	\$ 408,708	0.00%
35%	0	0%	9,909,278	0.00%	-	62,121	\$ 62,121	0.00%	\$ 408,708	0.00%
40%	0	0%	9,909,278	0.00%	-	62,121	\$ 62,121	0.00%	\$ 408,708	0.00%
45%	1	33%	9,909,278	0.00%	-	62,121	\$ 62,121	0.00%	\$ 408,708	0.00%
50%	1	33%	9,909,278	0.00%	-	62,121	\$ 62,121	0.00%	\$ 408,708	0.00%
55%	2	67%	12,089,335	22.00%	43,154	9,100	\$ 52,253	-15.88%	\$ 407,047	-0.41%
60%	2	67%	12,089,335	22.00%	43,154	9,100	\$ 52,253	-15.88%	\$ 403,934	-1.17%
65%	2	67%	12,089,335	22.00%	43,154	9,100	\$ 52,253	-15.88%	\$ 396,043	-3.10%
70%	2	67%	12,089,335	22.00%	43,154	9,100	\$ 52,253	-15.88%	\$ 388,153	-5.03%
75%	2	67%	12,089,335	22.00%	43,154	9,100	\$ 52,253	-15.88%	\$ 380,262	-6.96%

INPUT: This is the only cell where input must be provided

These cells in Row 11 refer to the Results tab and show results at the end of each run

The values here are pasted from the Row 11 to generate the graph below.



Inputs Used
 CSL (both) = 95%
 r (both) = 0.35
 v (both) = 0.05 \$/lbs
 LT (both) = 10 days
 Tki, Tkj, Tij = 0.0118 cents/lbs/mile