Logistics Network Design with Differentiated Delivery Lead-Time: Benefits and Insights

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***Abstract* — Most logistics network design models assume exogenous customer demand that is independent of the service time or level. This paper examines the benefits of segmenting demand according to lead-time sensitivity of customers. To capture lead-time sensitivity in the network design model, we use a facility grouping method to ensure that the different demand classes are satisfied on time. In addition, we perform a series of computational experiments to develop a set of managerial insights for the network design decision making process.**

***Index Terms* — Logistics Network Design, Demand Classes, Benefits, Insights**

I. INTRODUCTION

LOGISTICS network design is concerned with the determination of the number and location of warehouses and production plants, allocation of customer demand points to warehouses, and allocation of warehouses to production plants. The optimal configuration must be able to deliver the products to the customers at the least cost (commonly used objective) while satisfying the service level requirements. In most logistics network design models, the customer demand is exogenous and defined as a uniform quantity for each product. Such a uniform demand value does not exploit the possibility that different customers have different sensitivity to delivery lead-time. For example in the chemical dye industry, small textile mills tend to be more lead-time sensitive while the bigger textile mills are more price-sensitive, and would be enticed by price discount to accept a longer lead time. Thus, by designing a network to suit different demand classes, the network can be more efficient and network cost can be reduced.

This paper examines the benefits of segmenting demand according to lead-time sensitivity of customers, whereby the amount of demand depends on the delivery lead-time. For instance, consider an aggregate customer that might represent all of the customers from a region or zip code area. If, say, the logistics network can serve the region with a one-day delivery lead-time, then the network will be subject to some demand level, say 100 units per month. However, if the logistics network can only provide, say, a three-day delivery lead-time to the region, then the demand will drop, say, to 30 units per month, because it will lose the customers that require quicker delivery. We define lead-time sensitivity as the delay that the customer can tolerate from the time the order is placed to the receipt of the order. To capture lead-time sensitivity in the network design model, we use a facility grouping method to ensure that the different demand classes are satisfied on time. We will first formulate a model to allow for lead-time sensitivity, and then will use this model to generate managerial insights for the network design decision making process.

II. LITERATURE REVIEW

Logistics network design has been tackled as a facility *location problem* in the research arena. Location theory was first introduced in 1909 by Alfred Weber [1] who considered the problem of locating a single warehouse among customers to minimize total distance between warehouse and customers. Following this work, a lot of research work has emerged in varying forms. Tansel et al. [2 and 3] provide a survey of the network location problems based on a conceptual framework. They studied *p-center* and *p-median* problems and the computational order of the algorithms involved. They also discussed distance constrained problems, convexity concepts and multi-objective location problems. Brandeau and Chiu [4] provide a comprehensive study on the overview of

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representative problems in location research, where they have classified location problems according to the objective, decision variables and system parameters.

To ensure that demand at different customer locations is satisfied on time, network design models usually include time and/or distance constraints as service level requirements. In a specific type of location problems with distance constraints known as *covering problems*, the service level requirement is often represented as “the maximum distance between the customer and the facility”, or “the proportion of customers whose distance is no more than a given distance”. Examples of such works include, Patel [5] who modeled a social service center location problem as a *p-cover problem* where the objective is to minimize the maximum distance between customer and service center subject to budget and distance constraints. Moore and ReVelle [6] modeled the hierarchical service location problem as a *hierarchical covering problem* where the objective was to minimize the number of demand points not covered subject to fixed number of facilities and coverage constraints. Another approach for a service level requirement is to convert it into a product specific delivery delay bound, where the average time taken to deliver the product, summed over all customers and warehouses, must be less than the bound. This idea is discussed in Geoffrion and Graves [7].

Kolen [8] relaxed the distance constraint and solved the *minimum cost partial covering problem* where the objective was to minimize the facility setup costs and a penalty cost for not serving some demand points. In this case, the service level requirement is converted into a penalty cost in the objective function, for not satisfying demand.

In terms of solution methods for solving location problems with distance constraints, Francis et al. [9] established the necessary and sufficient conditions for distance constraints to be consistent, and presented a sequential location procedure to determine if a feasible solution exists for given distance constraints, and to find the solution if it exists. Moon and Chaudhry [10] examined a class of location problems with distance constraints and surveyed the solution techniques available. They also discussed the computational difficulties on solving such problems.

Another way to ensure that demand is satisfied on time is to include the time dimension in location problem. O’Kelly [11] addressed the location of two interacting hubs where the objective was to minimize the sum of travel times between every pair of customers. The optimal locations for the two hubs were obtained by generating optimal locations for all possible non-overlapping partitions of customers. Goldman [12] and Hakimi and Maheshwari [13] showed that for an objective function that minimizes the sum of travel times for a *k-center* problem, the optimal center location will be at the nodes of the graph. This result is particularly useful in guaranteed time distribution model, where the objective is to minimize the maximum travel time for k-center problem with interactions defined on tree graphs. Iyer and Ratliff [14] studied the location of accumulation points on tree networks for guaranteed time distribution, particularly for express mail service. Two cases were evaluated where in the first case, the accumulated flows between accumulation points pass through a global center in a centralized system, while in the second case the flows pass between the accumulation points directly. They provided an algorithm to locate a given number of accumulation points, allocate customers to them and provide the best time guarantee for both centralized and decentralized distribution systems. Another interesting piece of work is reported by Brimberg et al. [15] who formulated the football problem of positioning punt returners to maximize the number of punts caught as a location problem. Their model included the dimension of time and Euclidean distance, to study the number of returners to use (one or two) and their positions.

To our knowledge, there has been no research work on location problems that consider separate demand classes at each demand point where the classes differ in terms of their delivery lead-time requirements. In this paper we focus on designing a two-echelon distribution network with a hub at the first echelon and potential local warehouse locations at the second echelon. We differ from previous research in that, we assume that demand at each demand point can be separated into two classes based on their sensitivity to delivery lead time, namely demand with long delivery lead-time and demand with short delivery lead-time (abbreviated as LDLT and SDLT respectively). We then use a facility grouping method to ensure that the different demand classes are satisfied on time. SDLT can be satisfied only if delivery is made from a local warehouse (or in some cases, a nearby warehouse which can also fulfill the SDLT requirement). The key decision therefore is whether or not to open local warehouses to satisfy the SDLT demand, and if so, which ones to open. The amount of SDLT demand that can be satisfied, rather than lost, depends on which local warehouses are open.

III. MODEL, PARAMETERS AND ASSUMPTIONS

The two-echelon supply chain is depicted in Figure 1 with some of the parameters and decision variables. The model trades off the costs associated with setting up the network to satisfy demand of two different classes with the cost of losing the demand. We will use index k for the first echelon, namely the hub, and index j for the local warehouses; occasionally we will use index f to denote a facility, which applies to both echelons.

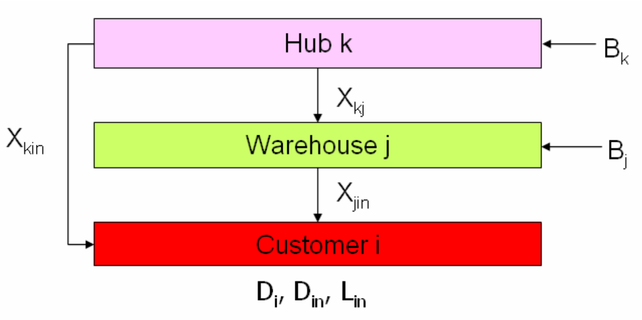


Figure 1: Two-echelon supply chain

Parameters

- Z_k, Z_j = fixed cost of hub k and warehouse j, respectively
- W_k, W_j = unit variable cost of facility k and j respectively
- H_k, H_j = unit inventory holding cost at facility k and j respectively
- B_k, B_j = external supply of product to facility k and j respectively
- DLT_{in} = delivery lead-time at location i where DLT_{i1} is short and DLT_{i2} is long (e.g. DLT_{i1} = 1 to 2 days, DLT_{i2} = 3 to 5 days)
- S_{fin} = binary parameter that indicates if facility f can serve customers at location i with a delivery lead-time that is less than or equal to DLT_{in}
- D_{in} = demand with delivery lead-time DLT_{in}
- D_i = total demand at location i
- L_{in} = unit lost sales cost for customers at location i with DLT_{in}
- C_{kj}^{LCL}, C_{kj}^{FCL} = Less-than-container load (LCL) and full-container-load (FCL) rate of shipping per unit of product from hub k to warehouse j respectively
- C_{ki}^{LCL}, C_{ki}^{FCL} = LCL and FCL rate of shipping per unit of product from hub k to customer i, respectively
- C_{ji}^{LCL}, C_{ji}^{FCL} = LCL and FCL rate of shipping per unit of product from warehouse j to customer i, respectively
- SF_{fi} = shipping frequency from facility f to customer i
- SF_{kj} = shipping frequency from hub k to warehouse j
- T = tonnage for FCL

Decision Variables

- Y_f = 0 if facility is closed and 1 if otherwise
- X_{kj} = quantity shipped from hub k to warehouse j
- X_{kin} = quantity shipped from hub k to customer i to satisfy demand with delivery lead-time, DLT_{in}
- X_{jin} = quantity shipped from warehouse j to customer i to satisfy demand with delivery lead-time, DLT_{in}

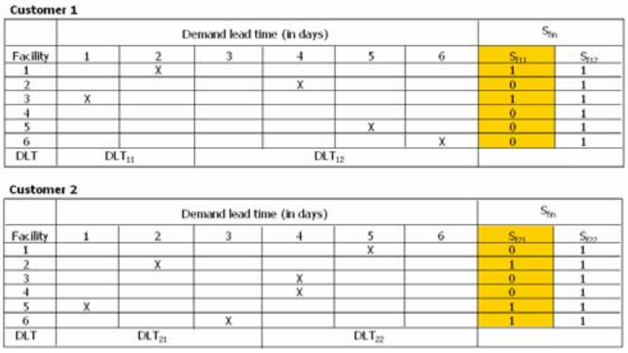
Assumptions

- Single product with deterministic demand
- We are given as input a shipping frequency for each O-D pair, which is the rate of shipments between the origin and destination. The quantity shipped per shipment is the same for each shipment between an O-D pair
- We assume a piecewise linear concave cost function with two-segment to model the opportunities for freight consolidation
- We approximate the inventory holding cost to be proportional to a linear function of the amount of flow through the facility
- We assume the inventory holding cost per unit is higher at local warehouse than at distribution hub
- We assume the shipping frequency is lower between the hub and local warehouse than between the local warehouse and customer.
- We ignore capacity constraints

Before we go into the model, let us understand the facility grouping method employed. Consider two customer locations served by 6 possible facilities as shown in Figure 2.

- At customer location 1, the delivery lead-time is split into two groups, where the short LT group DLT_{11} is between 1 to 2 days, and the long LT group DLT_{12} is between 3 to 6 days. The "X" indicates if the facility can serve the customer within the number of days. For example, facility 3 can serve customer location 1 in 1 day. As such. S_{f11} would be "1" for facilities 1 and 3 and "0" for the other facilities.
- At customer location 2, the delivery lead-time is split such that the short LT group DLT_{21} is between 1 to 3 days, and the long LT group DLT_{22} is between 4 to 6 days. Similarly, S_{f21} would be "1" for facilities 2, 5 and 6, and "0" for the other facilities.

We can extend this facility grouping method to consider any number of delivery lead-time grouping. We observe that we can define different short or long lead times for each customer location. Most importantly, it facilitates the inclusion of lead-time consideration in network modeling.



Customer 1

	Demand lead time (in days)						S_{fin}	
Facility	1	2	3	4	5	6	S_{f11}	S_{f12}
1		X					1	1
2				X			0	1
3	X						1	1
4							0	1
5					X		0	1
6						X	0	1
DLT	DLT_{11}		DLT_{12}					

Customer 2

	Demand lead time (in days)						S_{fin}	
Facility	1	2	3	4	5	6	S_{f21}	S_{f22}
1					X		0	1
2		X					1	1
3				X			0	1
4				X			0	1
5	X						1	1
6			X				1	1
DLT	DLT_{21}			DLT_{22}				

Figure 2: Facility Grouping Method Illustration

The model is described below.

Minimize Cost =

$$\sum_{f=1}^{F} Y_f Z_f$$

$$+\sum_{i=1}^{I}\sum_{f=1}^{F} X_{fi}(W_f + \frac{0.5H_f}{SF_{fi}})$$

$$+\sum_{i=1}^{I}\sum_{f=1}^{F}\left(X_{fi}^{LCL}C_{fi}^{LCL} + X_{fi}^{FCL}C_{fi}^{FCL}\right)SF_{fi}$$

$$+\sum_{j=1}^{J}\sum_{k=1}^{K} X_{kj}(W_k + W_j + \frac{0.5H_k}{SF_{kj}} + \frac{0.5H_j}{SF_{kj}})$$

$$+\sum_{j=1}^{J}\sum_{k=1}^{K}\left(X_{kj}^{LCL}C_{kj}^{LCL} + X_{kj}^{FCL}C_{kj}^{FCL}\right)SF_{kj}$$

$$+\sum_{i=1}^{I}\sum_{n=1}^{2} L_{in}\left(D_{in} - \sum_{f=1}^{F} X_{fin}S_{fin}\right)$$

Subject to,

$$\sum_{f=1}^{F} X_{fin}S_{fin} \le D_{in} \rightarrow \forall i, n \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

$$\sum_{n=1}^{2} X_{fin} = X_{fi} \rightarrow \forall i, f \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

$$X_{fi} \le Y_f D_i \rightarrow \forall i, f \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3a)$$

$$X_{kj} \le Y_k B_k \rightarrow \forall k \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3b)$$

$$\sum_{j=1}^{J} X_{kj} + \sum_{i=1}^{I} X_{ki} \le B_k \rightarrow \forall k \ldots\ldots\ldots\ldots\ldots\ldots (4a)$$

$$\sum_{i=1}^{I} X_{ji} \le \sum_{k=1}^{K} X_{kj} + B_j \rightarrow \forall j \ldots\ldots\ldots\ldots\ldots\ldots (4b)$$

$$\frac{X_{fi}}{SF_{fi}} = X_{fi}^{LCL} + X_{fi}^{FCL} \rightarrow \forall i, f \ldots\ldots\ldots\ldots\ldots\ldots (5a)$$

$$\frac{X_{kj}}{SF_{kj}} = X_{kj}^{LCL} + X_{kj}^{FCL} \rightarrow \forall k, j \ldots\ldots\ldots\ldots\ldots\ldots (5b)$$

$$T * R_{fi} \le X_{fi}^{FCL} \le M * R_{fi} \rightarrow \forall i, f \ldots\ldots\ldots\ldots (6a)$$

$$T * R_{kj} \le X_{kj}^{FCL} \le M * R_{kj} \rightarrow \forall k, j \ldots\ldots\ldots\ldots (6b)$$

$$Y_f, R_{fi}, R_{kj} \in \{0,1\}, \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

$$X_{fi}, X_{fi}^{LCL}, X_{fi}^{FCL}, X_{kj}, X_{kj}^{LCL}, X_{kj}^{FCL} \ge 0 \ldots\ldots\ldots\ldots (8)$$

The objective function trades off the cost of running the network to satisfy demand against the lost sales cost of not satisfying demand.

- First term – fixed cost
- Second term – variable cost and inventory holding cost involved in shipping product from facility to customer
- Third term – shipping cost involved in shipping product from facility to customer
- Fourth term – variable cost and inventory holding cost involved in shipping product from hub to warehouse
- Fifth term – shipping cost involved in shipping product from hub to warehouse
- Sixth term – lost sales cost when demand is not satisfied

The explanation for the constraints is as follows:

(1) ensures that quantity shipped is no more than the demand
(2) ensures that the amount shipped from facility f to customer i for each delivery lead-time equals the total quantity shipped out of facility f to customer i
(3) forces the binary decision variable Y_f
(4) ensures that the flow from each facility does not exceed the flow into the facility
(5) & (6) sets the shipment quantity per trip, either as LCL or FCL
(7) & (8) sets the decision variables to binary or real

IV. ANALYSIS AND RESULTS

A. *Benefits of Customer Segmentation*

The intent of this section is to illustrate the benefits of segmenting customers. We first consider a simple example involving one hub, one local warehouse and one customer location. Without segmenting the customers, the network will have the structure in either Case A or Case B as shown in Figure 3.

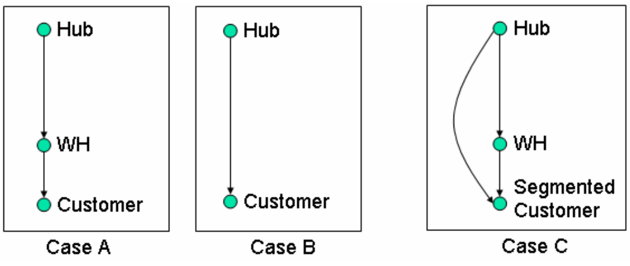


Figure 3: Segmenting Versus Not Segmenting Customers

In Case A, there is no customer segmentation and all customers are served by the local warehouse; Case A will result in excess logistics cost incurred to serve long LT demand using the local warehouse. In Case B, there is no customer segmentation and all customers are served directly by the hub. But since the hub cannot meet the delivery lead-time requirements for the short LT demand, this demand will be lost. In Case C, we are able to segment the customers. That is, the local warehouse serves the short LT customers, while the hub both serves directly the long LT customers and replenishes the local warehouse. Comparing cases A and C, there are savings in logistics costs, since it is cheaper to serve long LT demand from the hub. In comparing cases B and C, adding a local WH in Case C to serve the short LT customer must be balanced with the lost sales cost incurred in Case B. The network design with segmentation (Case C) permits more options and effectively incorporates both Case A and Case B.

To explore these tradeoffs further, we set up a computational experiment on a supply chain with one hub, five customer locations, and five corresponding warehouse locations, as shown in Figure 4. Four separate cases are run for each experimental setting,

- Case A = 0% LDLT, 100% SDLT
- Case B = 100% LDLT, 0% SDLT
- Case C1 = 30% LDLT, 70% SDLT
- Case C2 = 70% LDLT, 30% SDLT

In Case A and B, we assume we cannot segment demand. For Case A, we provide short delivery lead-time for all demand, regardless of whether this level of service is required or not. For Case B, we only provide a long delivery lead-time; as a consequence, in Case B we lose all of the short LT demand. In Cases C1 and C2, we assume we can segment the demand into two classes, where the cases differ in terms of the demand mix.

We compute the following measures;

a) $Measure^1$ is the percent network cost savings comparing Case C with Case A
b) $Measure^2$ is the percent network cost savings comparing Case C with Case B (where the cost for Case B is the network cost for Case B to serve the long LT demand, plus the lost sales cost for not serving the short LT demand.)

$$Measure^1 = \frac{NW_A - NW_C}{NW_A}$$

$$Measure^2 = \frac{NW_B - NW_C}{NW_B}$$

where NW represents the network cost.

We ran a total of 72 test problems by varying the following five parameters:

1. Demand variation among the 5 locations (high or low)
2. Facility fixed cost (high, medium or low)
3. Holding cost (high or low)
4. Facility grouping (1, 2 or 3 neighboring facility grouping for short LT)
5. Lost sales cost (high or low)

For each experiment, we obtained the results Cases A, B, C1 and C2 to compute the measures. For Case C1 and C2, we solve the optimization problem given in the previous section to determine which facilities to open, and which demand to serve. The experimental data used is given in Appendix 1.

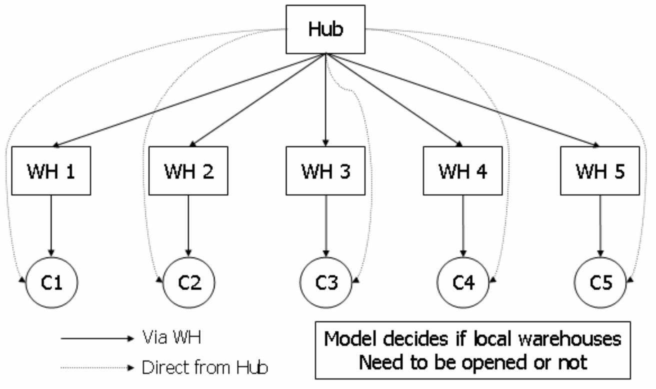


Figure 4: Experimental Supply Chain Model

The quantitative results (for detailed results, refer to Appendices 2 and 3) show that,

- by segmenting the demand (Cases C1 and C2), we can achieve a reduction in network cost, as compared to assuming 100% short LT demand (Case A) or assuming 100% long LT demand (Case B)
- when lost sales cost is low or when the percentage of long LT demand is high, Case C2 and Case B may result in the same network design, indicating that segmentation does not provide any benefits in these cases

Comparing Case C (segmented) to Case A (100% short LT demand), the percent cost savings increases as,

- the percent of LDLT increases
- facility grouping increases
- lost sales decreases
- holding cost increases
- fixed cost decreases
- demand variation increases

Comparing Case C (segmented) to Case B (100% long LT demand), the percent cost savings increases as,

- the percent of LDLT decreases
- facility grouping increases
- lost sales increases
- holding cost decreases
- fixed cost decreases
- demand variation increases

In conclusion, segmenting customers will result in more effective allocation of demand classes to facilities and reduces the network cost.

B. Managerial Insights

In this section, we highlight several important managerial insights for the network design decision making process. These insights are based on the 72 test problems which were run by varying the five parameters,

1. Demand variation among the 5 locations (high or low)
2. % of LDLT demand (high or low)
3. Facility fixed cost (high, medium or low)
4. Holding cost (high or low)
5. Facility grouping (1, 2 or 3 neighboring facility grouping for short LT)

For each test problem, we examine how the network design decisions change as we increase the lost sales cost, up until all the demand was satisfied. The experimental data used is the same as those defined in Appendix 1, and the results are given in Appendix 4.

A typical experimental result for a single facility grouping is shown in Figure 5. As we increase the lost sales cost, the network design would tend to include more local warehouses to satisfy demand as much as possible, until all demand is satisfied.

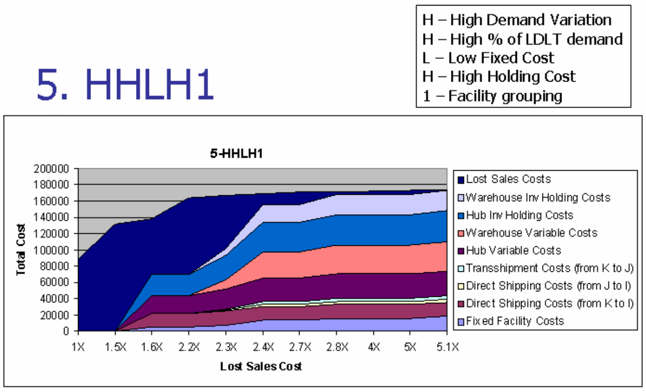


Figure 5: Example Experimental Result for Single-Facility Grouping

- At lost sales cost equal to 1X, all facilities are closed and all demand is lost
- At lost sales cost equal to 1.6X, the hub is opened to serve all LDLT demand at all customer locations
- At lost sales cost equal to 2.3X, WH3 is opened to serve SDLT at customer location 3
- At lost sales cost equal to 2.4X, WH1 and WH2 are opened to serve SDLT at customer locations 1 and 2 respectively
- At lost sales cost equal to 2.8X, WH5 is opened to serve SDLT at customer location 5
- At lost sales cost equal to 5.1X, the last warehouse WH4 is opened to serve SDLT at customer location 4.

Here X refers to a measure for the unit lost sales cost. See appendix for the definition of lost sales cost.

Our experiments yielded several interesting managerial insights.

First, we observed that the network cost reduces as facility grouping increases (see Appendix 5). This cost reduction is because more customer locations can be served from the same facility. This reduction is more significant from 1 to 2 grouping, than from 2 to 3 grouping.

Second, networks with lower holding costs can expect a higher percentage reduction in the network cost, with increased facility grouping (see Appendix 6). As facility grouping increases, the same facility can serve more customer locations and thus will result in holding more inventories, which takes greater advantage of the lower holding cost.

Third, networks with high facility fixed cost benefit the most from multiple-facility grouping (see Appendix 7). Multiple-facility grouping allows more demand to share the fixed cost of the facility. This sharing becomes more beneficial when the fixed cost is high.

Fourth, networks with *high* demand variation among customer locations, *high* percent of LDLT demand, *high* facility fixed cost and subjected to *single-facility* grouping, are most likely to incur lost sales. Due to high demand variation, some locations have very low demand. With high facility fixed cost, it takes extremely high lost sales cost to justify the opening of the local WH to serve such low demand points. As an example, in Run 1 – HHHH1, it takes lost sales cost to increase to 31.6X to make it worthwhile to open the last warehouse.

The most favorable network setting is “Low fixed cost, low holding cost and maximum-facility grouping”, while the most unfavorable network setting is “High fixed cost, high holding cost and single-facility grouping”.

- High demand variation among customer locations makes network planning difficult for locations with low demand. If such low demand locations have a high percent of long LT demand, it makes it even more unfavorable to open a local warehouse. Thus, the most favorable network setting will reduce the network cost.
- Low demand variation coupled with a low percent of long LT demand necessitates the opening of local warehouse. Thus, the most unfavorable network setting will drive the network cost up.

The decision to open or close a facility at a location is greatly affected by the fixed cost and/or amount of demand

- For high demand variation network, the locations with high demand coupled with low fixed cost have the highest priority to have their local warehouses opened
- For low demand variation network, locations with low fixed cost have the highest priority to have their local warehouses opened

For multiple-facility grouping, the decision to open or close a facility can change as the lost sales cost increases. As an example, for Run 17 – HHLH3, WH2 was opened initially to serve short LT demand for customer locations 1 to 4, but was later closed with WH3 opened to serve all demand. The flexibility provided by multiple-facility grouping can complicate the network design, as the optimal design can be quite sensitive to the lost sales cost.

Finally, maximum-facility grouping may not always result in a single warehouse serving all demand locations. For cases with a low percent of LDLT and low fixed cost, the optimal design might open more than one warehouse. As an example, for Run 35 – HLLH3, as the lost sales cost increases, the best design opens both WH1 to serve customer locations 1 and 2, and WH3 to serve customer locations 3, 4 and 5.

In conclusion,

- The model allows user to decide which facility to open or close in response to different lost sales cost.
- Multiple-facility grouping
    - Reduces network cost, especially for networks with high facility fixed cost
    - Reduces the possibility of incurring lost sales
    - May complicate network design decisions due to its sensitivity to the lost sales cost

V. FUTURE RESEARCH WORK

The model used assumes linear inventory holding cost in the objective function given by,

Inventory holding cost
= cycle stock inventory * unit inventory holding cost

$$= \frac{0.5X}{SF} H$$

Where,
H = unit inventory holding cost
X = flow quantity
SF = shipment frequency

Here, the safety stock inventory is ignored. This simplified representation is also used in the work by Jayaraman [16]. However, to give a better representation, one would include the safety stock inventory when computing the inventory holding cost. Thus, a measure of how well the linear model solution approximates the non-linear model solution will be useful.

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APPENDIX

Appendix 1 – Experimental Input Data

For Result A, a total of 72 test problems are run based on varying the five parameters,

1. Demand variation among the 5 locations (high or low)
2. Facility fixed cost (high, medium or low)
3. Holding cost (high or low)
4. Facility grouping (1, 2 or 3 neighboring facility grouping for short LT)
5. Lost sales cost (high or low)

For each test problem, we obtained the results for 0% (Case A), 30% (Case C1), 70% (Case C2) and 100% (Case B) LDLT to compute the measures.

	Demand variation	Fixed cost	WH holding cost	Facility grouping	Lost sales cost	Total # of runs
Levels	2	3	2	3	2	72

Similarly for Result B, a total of 72 experiments are run based on varying the five parameters,

1. Demand variation among the 5 locations (high or low)
2. % long LT demand (high or low)
3. Facility fixed cost (high, medium or low)
4. Holding cost (high or low)
5. Facility grouping (1, 2 or 3 neighboring facility grouping for short LT)

For each experiment, we investigate the network design decisions for increasing lost sales cost until all the demand is satisfied.

	Demand variation	% long LT demand	Fixed cost	WH holding cost	Facility grouping	Total # of runs
Levels	2	2	3	2	3	72

1. <u>Demand variation</u>

The demand values are randomly generated using the normal distribution given by,

$D_i \sim$ Normal (3000, 2500) for high demand variation

$D_i \sim$ Normal (3000, 300) for low demand variation

Thus, the generated values used for the experimental runs are,

	D_1	D_2	D_3	D_4	D_5
High	4962	3456	4844	340	1530
Low	3640	2947	2879	3188	2665

2. <u>Facility fixed cost</u>

Facilities are either leased or owned

- When owned, the fixed cost (FC) will be high and variable cost (VC) will be low
- When leased, the fixed cost (FC) will be low and the variable cost (VC) will be high

The values used for the experimental runs are,

	Hub	WH1	WH2	WH3	WH4	WH5
High FC	50000	30000	25000	25000	30000	27500
Low VC	1	2	2	2	2	2
Med FC	25000	15000	12500	12500	15000	13750
Med VC	1.5	3	3	3	3	3
Low FC	5000	3000	2500	2500	3000	2750
High VC	2	4	4	4	4	4

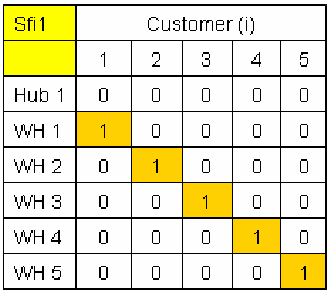
3. <u>Holding cost</u>

	Hub	WH1	WH2	WH3	WH4	WH5
High	5	10	10	10	10	10
Low	0.5	1	1	1	1	1

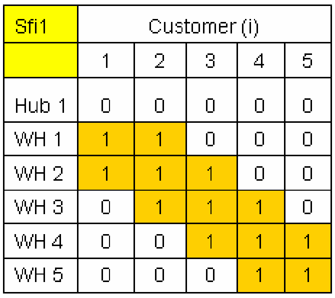
4. <u>Facility grouping</u>

This grouping method groups facilities which can serve the same location within the same short LT period into the same group. Three different sets of grouping are used as follow,

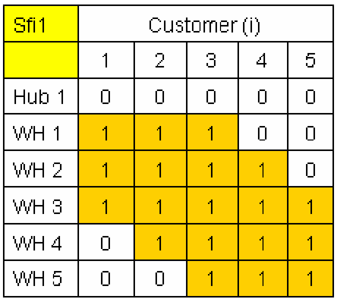
- 1-facility grouping (local WH only)
- 2-facility grouping (local WH plus neighboring WH on the left and right)
- 3-facility grouping (local WH plus 2 neighboring WH on the left and right)



Sfi1	Customer (i)				
	1	2	3	4	5
Hub 1	0	0	0	0	0
WH 1	1	0	0	0	0
WH 2	0	1	0	0	0
WH 3	0	0	1	0	0
WH 4	0	0	0	1	0
WH 5	0	0	0	0	1



Sfi1	Customer (i)				
	1	2	3	4	5
Hub 1	0	0	0	0	0
WH 1	1	1	0	0	0
WH 2	1	1	1	0	0
WH 3	0	1	1	1	0
WH 4	0	0	1	1	1
WH 5	0	0	0	1	1



Sfi1	Customer (i)				
	1	2	3	4	5
Hub 1	0	0	0	0	0
WH 1	1	1	1	0	0
WH 2	1	1	1	1	0
WH 3	1	1	1	1	1
WH 4	0	1	1	1	1
WH 5	0	0	1	1	1

From the grouping above, we can see that the possible favorable networks for 2-facility grouping are WH1 and WH4, WH2 and WH4, or WH2 and WH5. The optimal selection will be decided by the model. Where as for 3-facility grouping, it appears that the most favorable network is to open WH3 to serve all customer locations. However, the results of the runs (in Result B) show that in some cases, this selection may be the best.

5. <u>Lost sales cost</u>

Lost sales cost is defined as the profit forgone plus other perceived cost of not satisfying the customers. The perceived cost is usually very difficult to estimate. Therefore, the lost sales cost used here is N times the cost of sending a unit product from a facility to the customer directly from the hub or via a local warehouse. The values given in the table below are computed using high facility variable cost, low holding cost and LCL shipping cost. For high lost sales cost, we use 10X the values in the table; and for low lost sales cost, we use 3X the values in the table.

	Indirect via WH	Direct from hub
Customer 1	9.1	4
Customer 2	9.4	4.3
Customer 3	9.6	4.4
Customer 4	9.8	4.6
Customer 5	9.6	4.5

Other input parameters include,

1. Shipping cost from facility to customer

A two-segment piecewise linear shipping cost is used here, namely as LCL (less-than-container-load) and FCL (full-container-load).

a) LCL shipping cost from facility to customer

	Customer 1	Customer 2	Customer 3	Customer 4	Customer 5
Hub	1.5	1.8	1.9	2.1	2
WH 1	0.6	0.9	1	1.3	1.4
WH 2	0.8	0.7	0.9	1.1	1.2
WH 3	1	0.9	0.8	0.9	1
WH 4	1.3	1.1	0.9	0.8	0.9
WH 5	1.4	1.3	1.1	1	0.7

b) FCL shipping cost from facility to customer

	Customer 1	Customer 2	Customer 3	Customer 4	Customer 5
Hub	1.4	1.6	1.7	1.9	1.8
WH 1	0.4	0.7	0.8	1.1	1.2
WH 2	0.6	0.5	0.7	0.9	1
WH 3	0.8	0.7	0.6	0.7	0.8
WH 4	1.1	0.9	0.7	0.6	0.7
WH 5	1.2	1.1	0.9	0.8	0.5

2. Shipment frequency from facility to customer

In terms of shipment frequency, we assumed that the further the facility is from the customer location, the lower the frequency, and vice versa.

	Customer 1	Customer 2	Customer 3	Customer 4	Customer 5
Hub	1	1	1	1	1
WH 1	10	8	6	4	2
WH 2	8	10	8	6	4
WH 3	6	8	10	8	6
WH 4	4	6	8	10	8
WH 5	2	4	6	8	10

3. Shipping cost and shipment frequency from hub to facility

From hub to ..	WH 1	WH 2	WH 3	WH 4	WH 5
LCL cost	1	1.2	1.3	1.5	1.4
FCL cost	0.8	1	1.1	1.3	1.2
Shipment frequency	1	1	1	1	1

Appendix 2 – Network Cost Savings Comparing Network with Segmentation (Case C1 and C2) with Network which Assumes 100% Short LT Demand (Case A)

						Measure[1]	
Run #	DV	FC	HC	FG	LS	C1	C2
1	H	H	H	1	H	12.7%	29.7%
2	H	H	H	1	L	13.6%	38.7%
3	H	H	H	2	H	13.5%	31.6%
4	H	H	H	2	L	16.0%	37.4%
5	H	H	H	3	H	15.0%	35.1%
6	H	H	H	3	L	15.0%	35.1%
7	H	H	L	1	H	9.8%	23.3%
8	H	H	L	1	L	10.1%	27.2%
9	H	H	L	2	H	9.9%	23.2%
10	H	H	L	2	L	9.9%	30.4%
11	H	H	L	3	H	11.6%	27.3%
12	H	H	L	3	L	11.6%	27.3%
13	H	M	H	1	H	14.8%	36.6%
14	H	M	H	1	L	16.1%	39.4%
15	H	M	H	2	H	17.0%	39.7%
16	H	M	H	2	L	17.0%	42.1%
17	H	M	H	3	H	18.0%	42.0%
18	H	M	H	3	L	18.0%	42.0%
19	H	M	L	1	H	12.3%	31.2%
20	H	M	L	1	L	13.5%	33.9%
21	H	M	L	2	H	15.0%	35.1%
22	H	M	L	2	L	15.0%	36.7%
23	H	M	L	3	H	16.3%	38.2%
24	H	M	L	3	L	16.3%	38.2%
25	H	L	H	1	H	19.5%	45.4%
26	H	L	H	1	L	19.7%	46.1%
27	H	L	H	2	H	20.1%	46.9%
28	H	L	H	2	L	20.1%	46.9%
29	H	L	H	3	H	20.0%	47.1%
30	H	L	H	3	L	20.0%	47.1%
31	H	L	L	1	H	18.8%	44.0%
32	H	L	L	1	L	18.8%	44.7%
33	H	L	L	2	H	19.8%	46.1%
34	H	L	L	2	L	19.8%	46.1%
35	H	L	L	3	H	19.6%	46.6%
36	H	L	L	3	L	19.6%	46.6%
37	L	H	H	1	H	10.5%	24.7%
38	L	H	H	1	L	11.8%	42.9%
39	L	H	H	2	H	13.4%	31.7%
40	L	H	H	2	L	13.4%	32.6%
41	L	H	H	3	H	14.7%	35.0%
42	L	H	H	3	L	14.7%	35.0%
43	L	H	L	1	H	6.8%	16.2%
44	L	H	L	1	L	6.8%	30.2%
45	L	H	L	2	H	9.7%	23.3%
46	L	H	L	2	L	9.7%	23.3%
47	L	H	L	3	H	11.2%	27.0%
48	L	H	L	3	L	11.2%	27.0%
49	L	M	H	1	H	14.7%	34.5%
50	L	M	H	1	L	14.7%	39.6%
51	L	M	H	2	H	16.8%	39.7%
52	L	M	H	2	L	16.8%	39.7%
53	L	M	H	3	H	17.7%	41.8%
54	L	M	H	3	L	17.7%	41.8%
55	L	M	L	1	H	12.1%	28.5%
56	L	M	L	1	L	12.1%	28.5%
57	L	M	L	2	H	14.7%	35.1%
58	L	M	L	2	L	14.7%	35.1%
59	L	M	L	3	H	15.9%	37.9%
60	L	M	L	3	L	15.9%	37.9%
61	L	L	H	1	H	19.2%	45.1%
62	L	L	H	1	L	19.2%	45.1%
63	L	L	H	2	H	19.8%	46.8%
64	L	L	H	2	L	19.8%	46.8%
65	L	L	H	3	H	19.8%	47.2%
66	L	L	H	3	L	19.8%	47.2%
67	L	L	L	1	H	18.5%	43.6%
68	L	L	L	1	L	18.5%	43.6%
69	L	L	L	2	H	19.4%	46.0%
70	L	L	L	2	L	19.4%	46.0%
71	L	L	L	3	H	19.4%	46.6%
72	L	L	L	3	L	19.4%	46.6%

DV = demand variation
FC = fixed cost
HC = holding cost
FG = facility grouping
LS = lost sales cost

Appendix 3 – Network Cost Savings Comparing Network with Segmentation (Case C1 and C2) with Network which Assumes 100% Long LT Demand (Case B)

						Measure[2]		Local WH Opened[@]	
Run #	DV	FC	HC	FG	LS	C1	C2	C1	C2
1	H	H	H	1	H	66.7%	46.0%	1,2,3,5	1,2,3,5
2	H	H	H	1	L	12.0%	0.0%	1,2,3	Nil
3	H	H	H	2	H	73.5%	57.7%	2(1,2,3),5(4,5)	2(1,2,3),5(4,5)
4	H	H	H	2	L	26.2%	11.8%	2(1,2,3)	2(1,2,3)
5	H	H	H	3	H	75.8%	62.7%	3(1,2,3,4,5)	3(1,2,3,4,5)
6	H	H	H	3	L	30.3%	14.7%	3(1,2,3,4,5)	3(1,2,3,4,5)
7	H	H	L	1	H	74.4%	54.4%	1,2,3,5	1,2,3,5
8	H	H	L	1	L	30.8%	2.7%	1,2,3	3
9	H	H	L	2	H	81.4%	67.0%	2(1,2,3),5(4,5)	2(1,2,3),5(4,5)
10	H	H	L	2	L	45.7%	27.1%	2(1,2,3),5(4,5)	2(1,2,3)
11	H	H	L	3	H	83.8%	72.2%	3(1,2,3,4,5)	3(1,2,3,4,5)
12	H	H	L	3	L	52.7%	32.4%	3(1,2,3,4,5)	3(1,2,3,4,5)
13	H	M	H	1	H	71.2%	56.1%	1,2,3,4,5	1,2,3,5
14	H	M	H	1	L	17.6%	2.2%	1,2,3	1,3
15	H	M	H	2	H	75.0%	62.9%	2(1,2,3),5(4,5)	2(1,2,3),5(4,5)
16	H	M	H	2	L	25.2%	14.1%	2(1,2,3),5(4,5)	2(1,2,3)
17	H	M	H	3	H	76.1%	65.3%	3(1,2,3,4,5)	3(1,2,3,4,5)
18	H	M	H	3	L	28.3%	16.6%	3(1,2,3,4,5)	3(1,2,3,4,5)
19	H	M	L	1	H	79.2%	65.4%	1,2,3,4,5	1,2,3,5
20	H	M	L	1	L	39.7%	17.1%	1,2,3,5	1,2,3
21	H	M	L	2	H	83.2%	72.7%	2(1,2,3),5(4,5)	2(1,2,3),5(4,5)
22	H	M	L	2	L	48.7%	31.3%	2(1,2,3),5(4,5)	2(1,2,3)
23	H	M	L	3	H	84.3%	75.4%	3(1,2,3,4,5)	3(1,2,3,4,5)
24	H	M	L	3	L	52.1%	36.4%	3(1,2,3,4,5)	3(1,2,3,4,5)
25	H	L	H	1	H	75.2%	65.2%	1,2,3,4,5	1,2,3,4,5
26	H	L	H	1	L	23.2%	13.6%	1,2,3,5	1,2,3,5
27	H	L	H	2	H	75.8%	66.7%	2(1,2,3),5(4,5)	2(1,2,3),5(4,5)
28	H	L	H	2	L	24.8%	16.3%	2(1,2,3),5(4,5)	2(1,2,3),5(4,5)
29	H	L	H	3	H	75.9%	67.0%	1(1,2),3(3,4,5)	3(1,2,3,4,5)
30	H	L	H	3	L	25.2%	17.1%	1(1,2),3(3,4,5)	3(1,2,3,4,5)
31	H	L	L	1	H	83.4%	75.4%	1,2,3,4,5	1,2,3,4,5
32	H	L	L	1	L	47.5%	33.8%	1,2,3,4,5	1,2,3,5
33	H	L	L	2	H	84.1%	77.0%	2(1,2,3),5(4,5)	2(1,2,3),5(4,5)
34	H	L	L	2	L	49.6%	37.6%	2(1,2,3),5(4,5)	2(1,2,3),5(4,5)
35	H	L	L	3	H	84.2%	77.5%	1(1,2,3),3(4,5)	3(1,2,3,4,5)
36	H	L	L	3	L	50.0%	38.7%	1(1,2,3),3(4,5)	3(1,2,3,4,5)

						Measure[2]		Local WH Opened[@]	
Run #	DV	FC	HC	FG	LS	C1	C2	C1	C2
37	L	H	H	1	H	66.0%	42.5%	1,2,3,4,5	1,2,3,4,5
38	L	H	H	1	L	3.7%	0.0%	Nil (even Hub)	Nil
39	L	H	H	2	H	73.6%	58.1%	2(1,2,3),5(4,5)	2(1,2,3),5(4,5)
40	L	H	H	2	L	24.1%	5.2%	2(1,2,3),5(4,5)	2(1,2,3)
41	L	H	H	3	H	75.9%	63.0%	3(1,2,3,4,5)	3(1,2,3,4,5)
42	L	H	H	3	L	30.7%	15.2%	3(1,2,3,4,5)	3(1,2,3,4,5)
43	L	H	L	1	H	73.8%	50.8%	1,2,3,4,5	1,2,3,4,5
44	L	H	L	1	L	23.2%	0.0%	1,2,3,4,5	Nil
45	L	H	L	2	H	81.6%	67.3%	2(1,2,3),5(4,5)	2(1,2,3),5(4,5)
46	L	H	L	2	L	45.9%	20.2%	2(1,2,3),5(4,5)	2(1,2,3),5(4,5)
47	L	H	L	3	H	84.0%	72.5%	3(1,2,3,4,5)	3(1,2,3,4,5)
48	L	H	L	3	L	53.0%	32.9%	3(1,2,3,4,5)	3(1,2,3,4,5)
49	L	M	H	1	H	71.4%	55.0%	1,2,3,4,5	1,2,3,4,5
50	L	M	H	1	L	14.1%	0.0%	1,2,3,4,5	Nil
51	L	M	H	2	H	75.2%	63.1%	2(1,2,3),5(4,5)	2(1,2,3),5(4,5)
52	L	M	H	2	L	25.5%	11.2%	2(1,2,3),5(4,5)	2(1,2,3),5(4,5)
53	L	M	H	3	H	76.2%	65.6%	3(1,2,3,4,5)	3(1,2,3,4,5)
54	L	M	H	3	L	28.6%	17.0%	3(1,2,3,4,5)	3(1,2,3,4,5)
55	L	M	L	1	H	79.4%	64.3%	1,2,3,4,5	1,2,3,4,5
56	L	M	L	1	L	36.9%	7.8%	1,2,3,4,5	1,2,3,4,5
57	L	M	L	2	H	83.3%	72.9%	2(1,2,3),5(4,5)	2(1,2,3),5(4,5)
58	L	M	L	2	L	48.8%	29.9%	2(1,2,3),5(4,5)	2(1,2,3),5(4,5)
59	L	M	L	3	H	84.4%	75.6%	3(1,2,3,4,5)	3(1,2,3,4,5)
60	L	M	L	3	L	52.3%	36.8%	3(1,2,3,4,5)	3(1,2,3,4,5)
61	L	L	H	1	H	75.3%	65.2%	1,2,3,4,5	1,2,3,4,5
62	L	L	H	1	L	23.2%	12.6%	1,2,3,4,5	1,2,3,4,5
63	L	L	H	2	H	75.9%	66.8%	2(1,2,3),5(4,5)	2(1,2,3),5(4,5)
64	L	L	H	2	L	25.1%	16.7%	2(1,2,3),5(4,5)	2(1,2,3),5(4,5)
65	L	L	H	3	H	75.9%	67.2%	1(1,2),3(3,4,5)	3(1,2,3,4,5)
66	L	L	H	3	L	25.3%	17.5%	1(1,2),3(3,4,5)	3(1,2,3,4,5)
67	L	L	L	1	H	83.4%	75.3%	1,2,3,4,5	1,2,3,4,5
68	L	L	L	1	L	47.5%	32.9%	1,2,3,4,5	1,2,3,4,5
69	L	L	L	2	H	84.1%	77.1%	2(1,2,3),5(4,5)	2(1,2,3),5(4,5)
70	L	L	L	2	L	49.6%	37.8%	2(1,2,3),5(4,5)	2(1,2,3),5(4,5)
71	L	L	L	3	H	84.2%	77.5%	3(1,2,3,4,5)	3(1,2,3,4,5)
72	L	L	L	3	L	50.0%	39.0%	3(1,2,3,4,5)	3(1,2,3,4,5)

DV = demand variation
FC = fixed cost
HC = holding cost
FG = facility grouping
LS = lost sales cost

@ For 1-facility grouping, each local WH serves its corresponding customer location only. For 2- and 3-facility grouping, the numbers in parentheses represents the customer locations served by the warehouse which is opened. For example in Run # 3 - for both 30% LDLT and 70% LDLT, WH2 is opened to serve customer locations 1,2 and 3; while WH5 is opened to serve customer locations 4 and 5.

Special cases occur in Runs # 2, 38, 44 and 49 as shown below,

						Measure[2]		**Local WH Opened**[@]	
Run #	DV	FC	HC	FG	LS	C1	C2	C1	C2
2	H	H	H	1	L	12.0%	0.0%	1,2,3	Nil
38	L	H	H	1	L	3.7%	0.0%	Nil (even Hub)	Nil
44	L	H	L	1	L	23.2%	0.0%	1,2,3,4,5	Nil
50	L	M	H	1	L	14.1%	0.0%	1,2,3,4,5	Nil

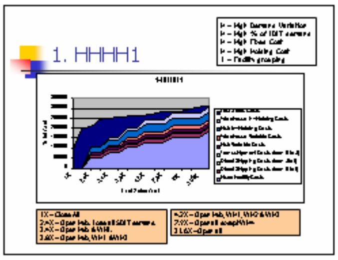
When the lost sales cost is low, and the percent of long LT demand is high (Case C2), the resulting network design was to only open the hub and close all local warehouses. This is the same network design for Case B. In these special cases, segmenting the customers does not provide much benefit at all.

For Run # 38, segmenting the demand with 30% long LT demand (Case C1), the resulting network was to close all facilities including the hub and lose all demand. For Case B, the network was still to open the hub to serve the long LT demand. After adjusting for potential lost sales cost for Case B, Case C1 is still better than Case B.

Appendix 4 – Network Design Decisions in Response to Increasing Lost Sales Cost

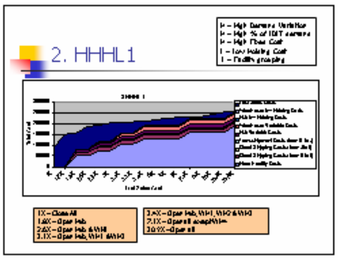
Parameter	**1**	**2**	**3**	**4**	**5**
Run #	DV	% LDLT	FC	HC	FG
1	H	H	H	H	1
2	H	H	H	L	1
3	H	H	M	H	1
4	H	H	M	L	1
5	H	H	L	H	1
6	H	H	L	L	1
7	H	H	H	H	2
8	H	H	H	L	2
9	H	H	M	H	2
10	H	H	M	L	2
11	H	H	L	H	2
12	H	H	L	L	2
13	H	H	H	H	3
14	H	H	H	L	3
15	H	H	M	H	3
16	H	H	M	L	3
17	H	H	L	H	3
18	H	H	L	L	3
19	H	L	H	H	1
20	H	L	H	L	1
21	H	L	M	H	1
22	H	L	M	L	1
23	H	L	L	H	1
24	H	L	L	L	1
25	H	L	H	H	2
26	H	L	H	L	2
27	H	L	M	H	2
28	H	L	M	L	2
29	H	L	L	H	2
30	H	L	L	L	2
31	H	L	H	H	3
32	H	L	H	L	3
33	H	L	M	H	3
34	H	L	M	L	3
35	H	L	L	H	3
36	H	L	L	L	3
37	L	H	H	H	1
38	L	H	H	L	1
39	L	H	M	H	1
40	L	H	M	L	1
41	L	H	L	H	1
42	L	H	L	L	1
43	L	H	H	H	2
44	L	H	H	L	2
45	L	H	M	H	2
46	L	H	M	L	2
47	L	H	L	H	2
48	L	H	L	L	2
49	L	H	H	H	3
50	L	H	H	L	3
51	L	H	M	H	3
52	L	H	M	L	3
53	L	H	L	H	3
54	L	H	L	L	3
55	L	L	H	H	1
56	L	L	H	L	1
57	L	L	M	H	1
58	L	L	M	L	1
59	L	L	L	H	1
60	L	L	L	L	1
61	L	L	H	H	2
62	L	L	H	L	2
63	L	L	M	H	2
64	L	L	M	L	2
65	L	L	L	H	2
66	L	L	L	L	2
67	L	L	H	H	3
68	L	L	H	L	3
69	L	L	M	H	3
70	L	L	M	L	3
71	L	L	L	H	3
72	L	L	L	L	3

DV = demand variation
% LDLT = % of long demand LT demand
FC = fixed cost
HC = holding cost
FG = facility grouping



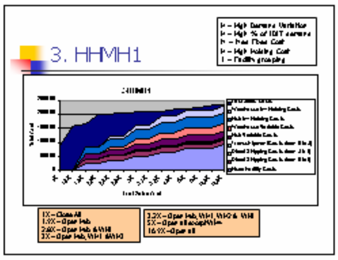
1. HHHH1

H – High Demand Variation
H – High % of IDIT demand
H – High Fixed Cost
H – High Holding Cost
1 – Facility grouping



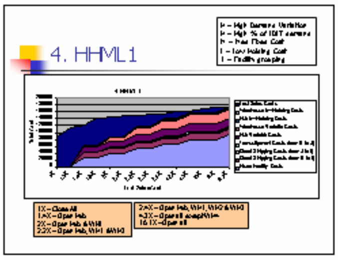
2. HHHL1

H – High Demand Variation
H – High % of IDIT demand
H – High Fixed Cost
L – Low Holding Cost
1 – Facility grouping



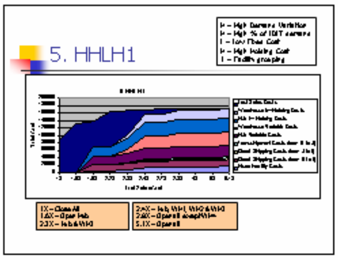
3. HHMH1

H – High Demand Variation
H – High % of IDIT demand
M – Med Fixed Cost
H – High Holding Cost
1 – Facility grouping



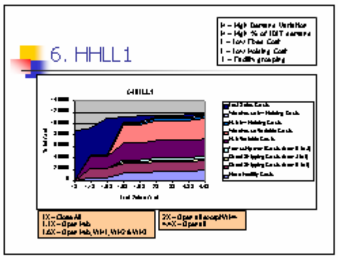
4. HHML1

H – High Demand Variation
H – High % of IDIT demand
M – Med Fixed Cost
L – Low Holding Cost
1 – Facility grouping



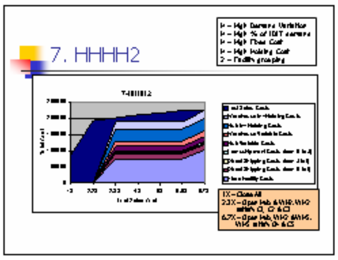
5. HHLH1

H – High Demand Variation
H – High % of IDIT demand
L – Low Fixed Cost
H – High Holding Cost
1 – Facility grouping



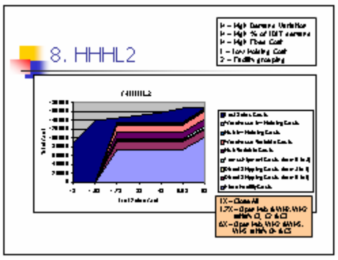
6. HHLL1

H – High Demand Variation
H – High % of IDIT demand
L – Low Fixed Cost
L – Low Holding Cost
1 – Facility grouping



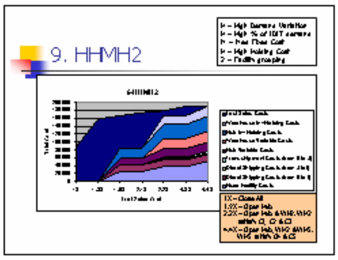
7. HHHH2

H – High Demand Variation
H – High % of IDIT demand
H – High Fixed Cost
H – High Holding Cost
2 – Facility grouping



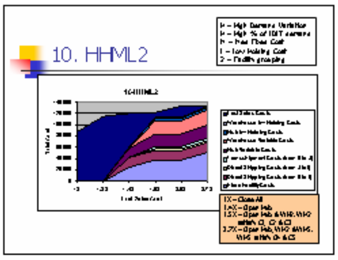
8. HHHL2

H – High Demand Variation
H – High % of IDIT demand
H – High Fixed Cost
L – Low Holding Cost
2 – Facility grouping



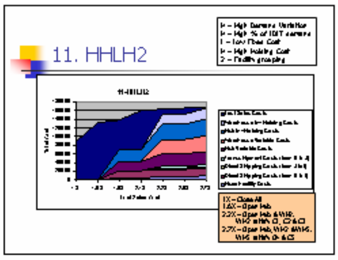
9. HHMH2

H – High Demand Variation
H – High % of IDIT demand
M – Med Fixed Cost
H – High Holding Cost
2 – Facility grouping



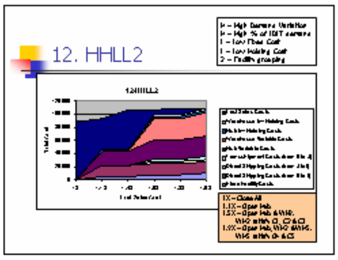
10. HHML2

H – High Demand Variation
H – High % of IDIT demand
M – Med Fixed Cost
L – Low Holding Cost
2 – Facility grouping



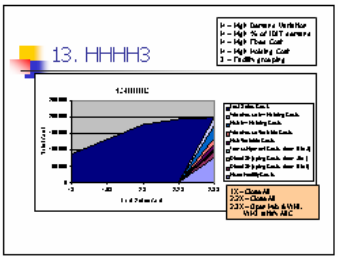
11. HHLH2

H – High Demand Variation
H – High % of IDIT demand
L – Low Fixed Cost
H – High Holding Cost
2 – Facility grouping



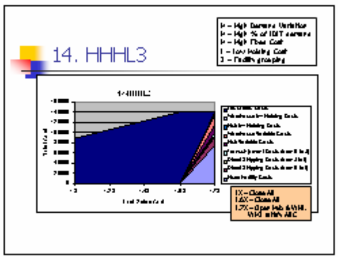
12. HHLL2

H – High Demand Variation
H – High % of IDIT demand
L – Low Fixed Cost
L – Low Holding Cost
2 – Facility grouping



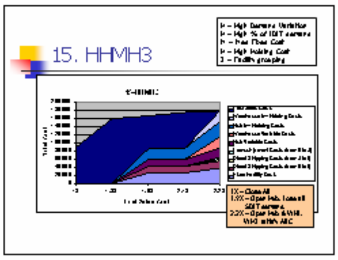
13. HHHH3

H – High Demand Variation
H – High % of IDIT demand
H – High Fixed Cost
H – High Holding Cost
3 – Facility grouping



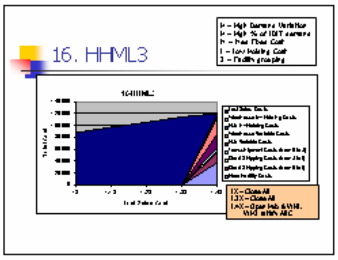
14. HHHL3

H – High Demand Variation
H – High % of IDIT demand
H – High Fixed Cost
L – Low Holding Cost
3 – Facility grouping

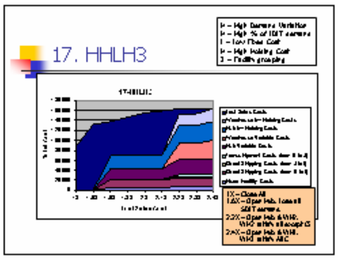


15. HHMH3

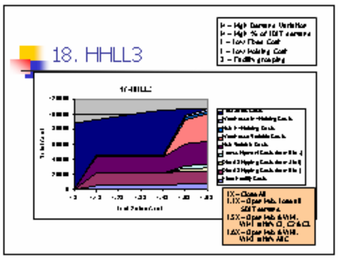
H – High Demand Variation
H – High % of IDIT demand
M – Med Fixed Cost
H – High Holding Cost
3 – Facility grouping



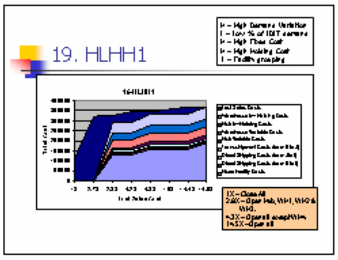
16. HHML3



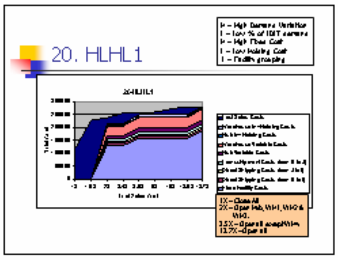
17. HHLH3



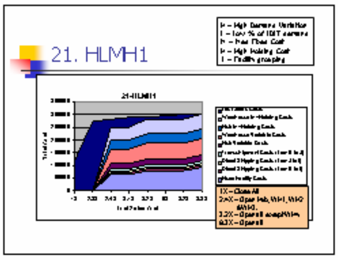
18. HHLL3



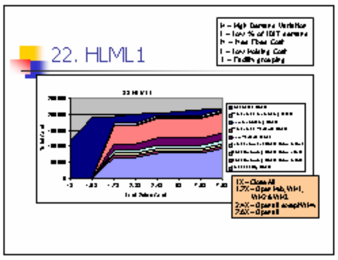
19. HLHH1



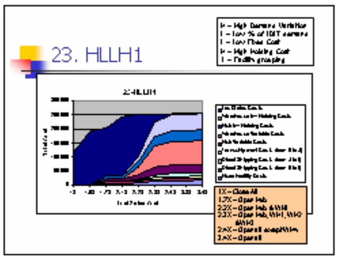
20. HLHL1



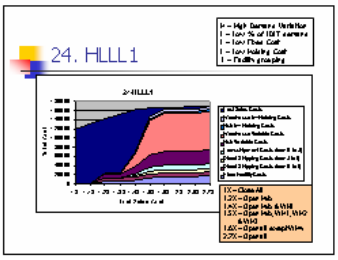
21. HLMH1



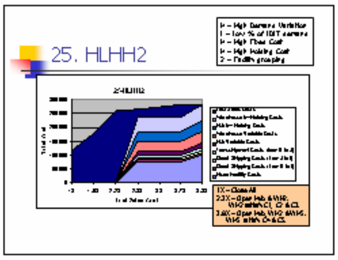
22. HLML1



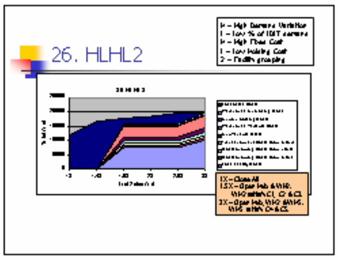
23. HLLH1



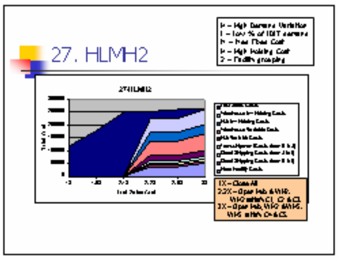
24. HLLL1



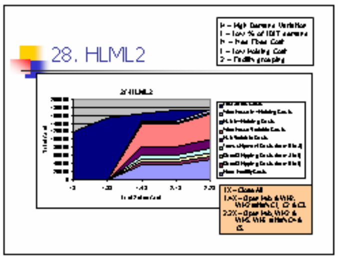
25. HLHH2



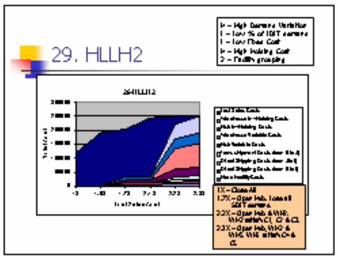
26. HLHL2



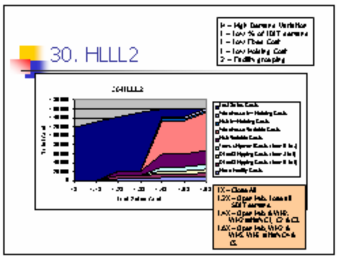
27. HLMH2



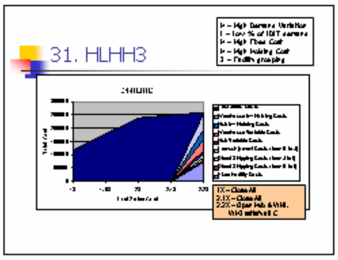
28. HLML2

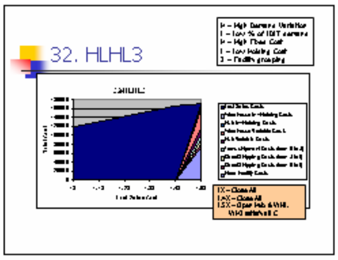


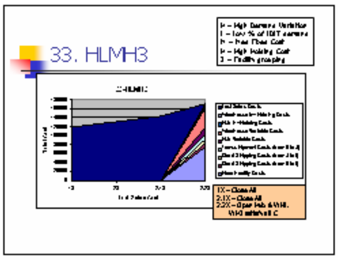
29. HLLH2

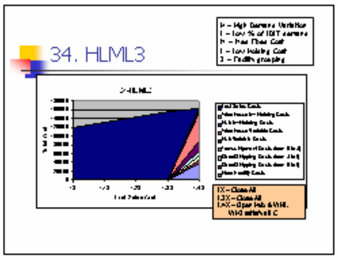


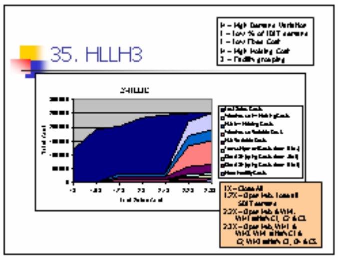
30. HLLL2

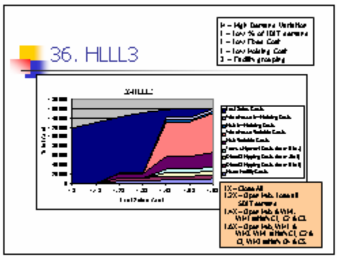

31. HLHH3
H – High Demand Variation
L – Low % of IDIT demand
H – High Fixed Cost
H – High Holding Cost
3 – Facility grouping

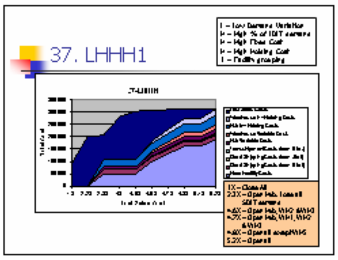

32. HLHL3
H – High Demand Variation
L – Low % of IDIT demand
H – High Fixed Cost
L – Low Holding Cost
3 – Facility grouping

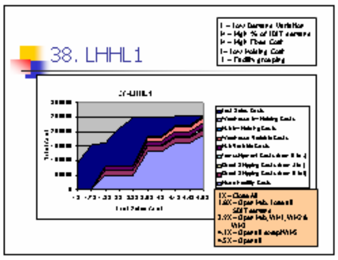

33. HLMH3
H – High Demand Variation
L – Low % of IDIT demand
M – Med Fixed Cost
H – High Holding Cost
3 – Facility grouping

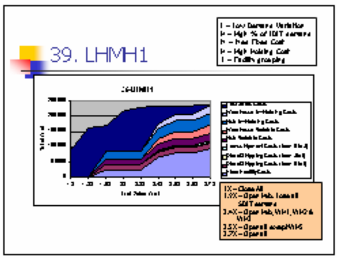

34. HLML3
H – High Demand Variation
L – Low % of IDIT demand
M – Med Fixed Cost
L – Low Holding Cost
3 – Facility grouping

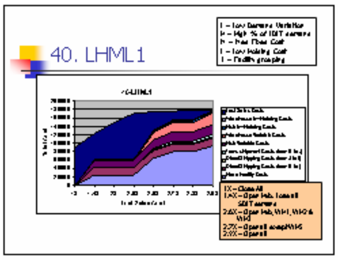

35. HLLH3
H – High Demand Variation
L – Low % of IDIT demand
L – Low Fixed Cost
H – High Holding Cost
3 – Facility grouping

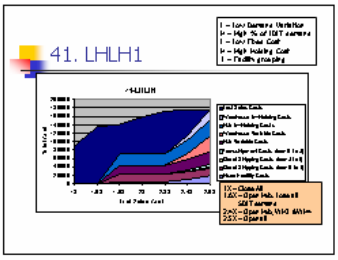

36. HLLL3
H – High Demand Variation
L – Low % of IDIT demand
L – Low Fixed Cost
L – Low Holding Cost
3 – Facility grouping

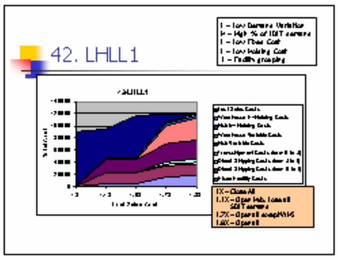

37. LHHH1
L – Low Demand Variation
H – High % of IDIT demand
H – High Fixed Cost
H – High Holding Cost
1 – Facility grouping

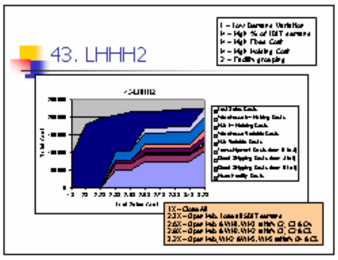

38. LHHL1
L – Low Demand Variation
H – High % of IDIT demand
H – High Fixed Cost
L – Low Holding Cost
1 – Facility grouping

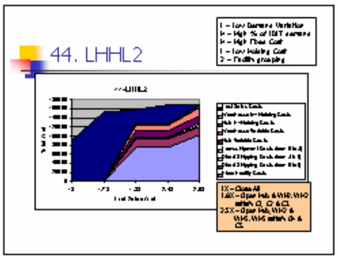

39. LHMH1
L – Low Demand Variation
H – High % of IDIT demand
M – Med Fixed Cost
H – High Holding Cost
1 – Facility grouping

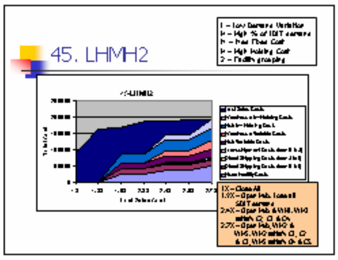

40. LHML1
L – Low Demand Variation
H – High % of IDIT demand
M – Med Fixed Cost
L – Low Holding Cost
1 – Facility grouping

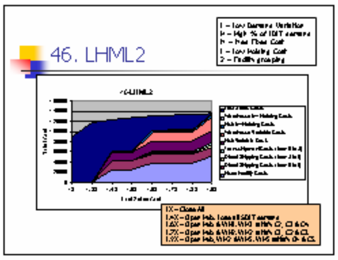

41. LHLH1
L – Low Demand Variation
H – High % of IDIT demand
L – Low Fixed Cost
H – High Holding Cost
1 – Facility grouping


42. LHLL1
L – Low Demand Variation
H – High % of IDIT demand
L – Low Fixed Cost
L – Low Holding Cost
1 – Facility grouping


43. LHHH2
L – Low Demand Variation
H – High % of IDIT demand
H – High Fixed Cost
H – High Holding Cost
2 – Facility grouping


44. LHHL2
L – Low Demand Variation
H – High % of IDIT demand
H – High Fixed Cost
L – Low Holding Cost
2 – Facility grouping

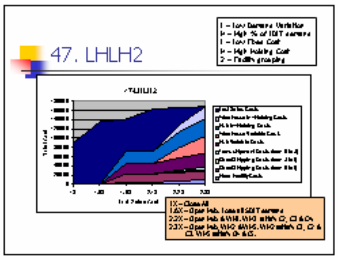

45. LHMH2
L – Low Demand Variation
H – High % of IDIT demand
M – Med Fixed Cost
H – High Holding Cost
2 – Facility grouping



46. LHML2

L – Low Demand Variation
H – High % of IDIT customers
M – Med Fixed Cost
L – Low Holding Cost
2 – Facility grouping

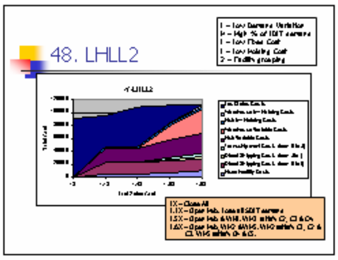
1X – Close All



47. LHLH2

L – Low Demand Variation
H – High % of IDIT customers
L – Low Fixed Cost
H – High Holding Cost
2 – Facility grouping

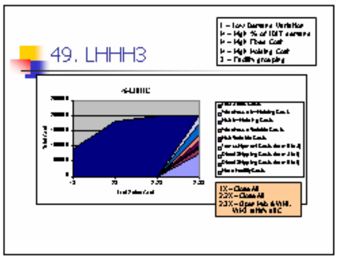
1X – Close All



48. LHLL2

L – Low Demand Variation
H – High % of IDIT customers
L – Low Fixed Cost
L – Low Holding Cost
2 – Facility grouping

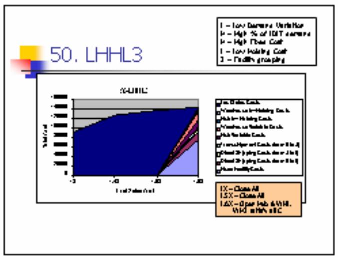
1X – Close All



49. LHHH3

L – Low Demand Variation
H – High % of IDIT customers
H – High Fixed Cost
H – High Holding Cost
3 – Facility grouping

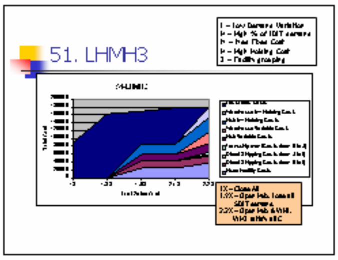
1X – Close All
2.2X – Close All



50. LHHL3

L – Low Demand Variation
H – High % of IDIT customers
H – High Fixed Cost
L – Low Holding Cost
3 – Facility grouping

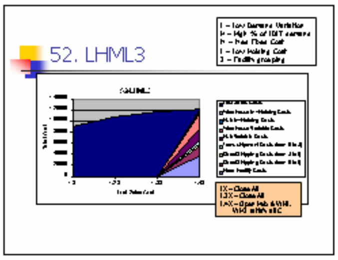
1X – Close All
1.5X – Close All



51. LHMH3

L – Low Demand Variation
H – High % of IDIT customers
M – Med Fixed Cost
H – High Holding Cost
3 – Facility grouping

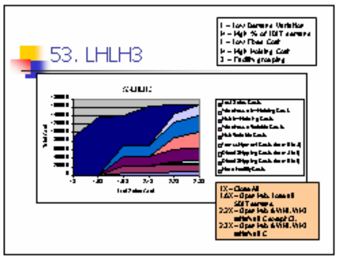
1X – Close All



52. LHML3

L – Low Demand Variation
H – High % of IDIT customers
M – Med Fixed Cost
L – Low Holding Cost
3 – Facility grouping

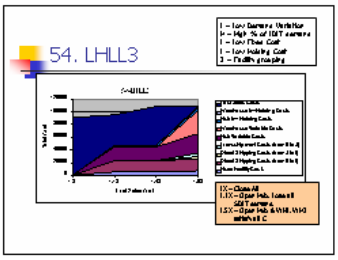
1X – Close All
1.3X – Close All



53. LHLH3

L – Low Demand Variation
H – High % of IDIT customers
L – Low Fixed Cost
H – High Holding Cost
3 – Facility grouping

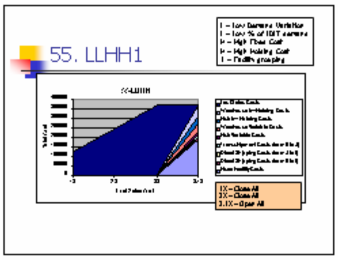
1X – Close All



54. LHLL3

L – Low Demand Variation
H – High % of IDIT customers
L – Low Fixed Cost
L – Low Holding Cost
3 – Facility grouping

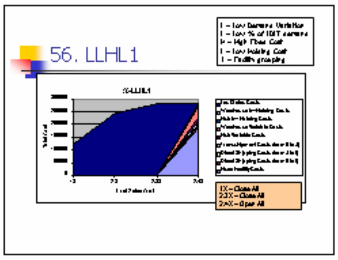
1X – Close All



55. LLHH1

L – Low Demand Variation
L – Low % of IDIT customers
H – High Fixed Cost
H – High Holding Cost
1 – Facility grouping

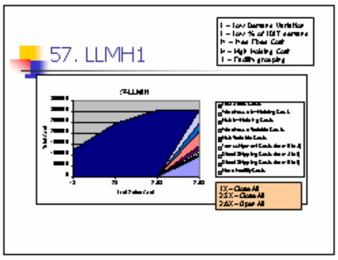
1X – Close All
2X – Close All
3.1X – Open All



56. LLHL1

L – Low Demand Variation
L – Low % of IDIT customers
H – High Fixed Cost
L – Low Holding Cost
1 – Facility grouping

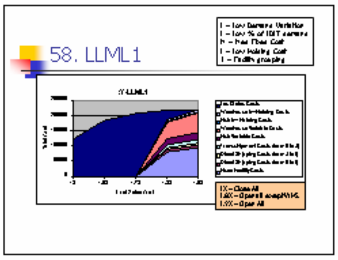
1X – Close All
2.3X – Close All
2.4X – Open All



57. LLMH1

L – Low Demand Variation
L – Low % of IDIT customers
M – Med Fixed Cost
H – High Holding Cost
1 – Facility grouping

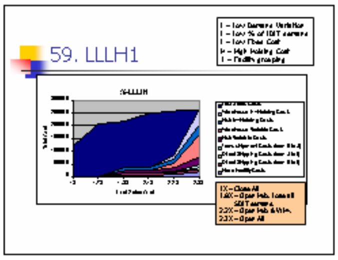
1X – Close All
2.5X – Close All
2.6X – Open All



58. LLML1

L – Low Demand Variation
L – Low % of IDIT customers
M – Med Fixed Cost
L – Low Holding Cost
1 – Facility grouping

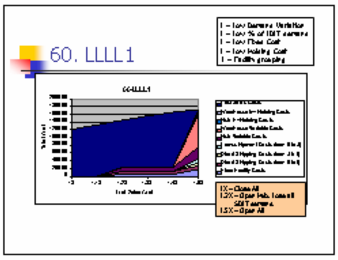
1X – Close All
1.9X – Open All



59. LLLH1

L – Low Demand Variation
L – Low % of IDIT customers
L – Low Fixed Cost
H – High Holding Cost
1 – Facility grouping

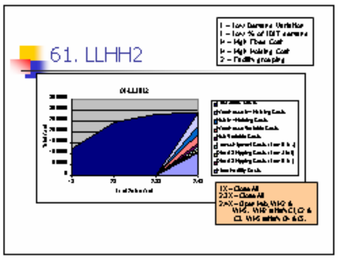
1X – Close All
2.3X – Open All



60. LLLL1

L – Low Demand Variation
L – Low % of IDIT customers
L – Low Fixed Cost
L – Low Holding Cost
1 – Facility grouping

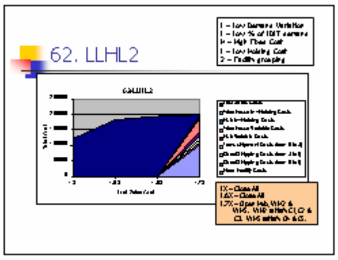
1X – Close All
1.5X – Open All



61. LLHH2

L – Low Demand Variation
L – Low % of IDIT demand
H – High Fixed Cost
H – High Holding Cost
2 – Facility grouping

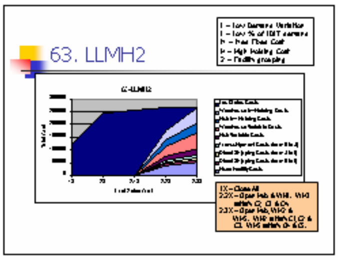
1X – Close All
2.3X – Close All
2.4X – Open Hub, WH2 & WH5. WH2 within C1, C2 & C3. WH5 within C4 & C5.



62. LLHL2

L – Low Demand Variation
L – Low % of IDIT demand
H – High Fixed Cost
L – Low Holding Cost
2 – Facility grouping

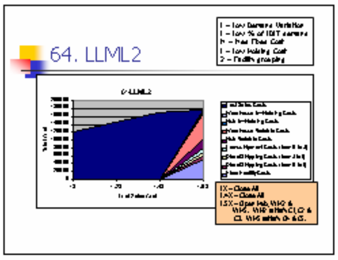
1X – Close All
1.6X – Close All
1.7X – Open Hub, WH2 & WH5. WH2 within C1, C2 & C3. WH5 within C4 & C5.



63. LLMH2

L – Low Demand Variation
L – Low % of IDIT demand
M – Med Fixed Cost
H – High Holding Cost
2 – Facility grouping

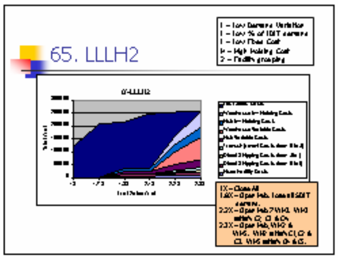
1X – Close All
2.2X – Open Hub & WH1. WH1 within C2, C3 & C4.
2.3X – Open Hub, WH2 & WH5. WH2 within C1, C2 & C3. WH5 within C4 & C5.



64. LLML2

L – Low Demand Variation
L – Low % of IDIT demand
M – Med Fixed Cost
L – Low Holding Cost
2 – Facility grouping

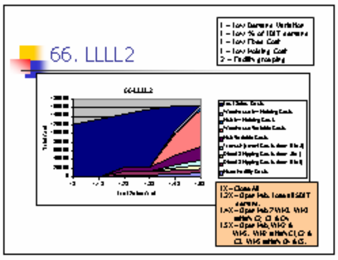
1X – Close All
1.4X – Close All
1.5X – Open Hub, WH2 & WH5. WH2 within C1, C2 & C3. WH5 within C4 & C5.



65. LLLH2

L – Low Demand Variation
L – Low % of IDIT demand
L – Low Fixed Cost
H – High Holding Cost
2 – Facility grouping

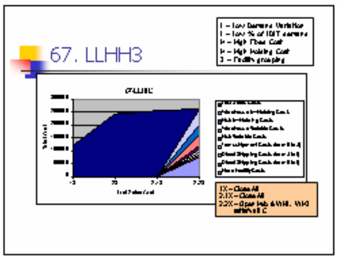
1X – Close All
1.8X – Open Hub. Lose all SDIT demand.
2.2X – Open Hub 7 WH1. WH1 within C2, C3 & C4.
2.3X – Open Hub, WH2 & WH5. WH2 within C1, C2 & C3. WH5 within C4 & C5.



66. LLLL2

L – Low Demand Variation
L – Low % of IDIT demand
L – Low Fixed Cost
L – Low Holding Cost
2 – Facility grouping

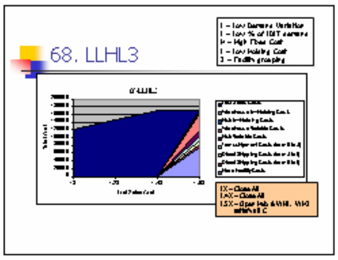
1X – Close All
1.2X – Open Hub. Lose all SDIT demand.
1.4X – Open Hub 7 WH1. WH1 within C2, C3 & C4.
1.5X – Open Hub, WH2 & WH5. WH2 within C1, C2 & C3. WH5 within C4 & C5.



67. LLHH3

L – Low Demand Variation
L – Low % of IDIT demand
H – High Fixed Cost
H – High Holding Cost
3 – Facility grouping

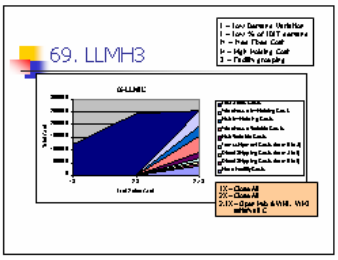
1X – Close All
2.1X – Close All
2.2X – Open Hub & WH1. WH1 within all C



68. LLHL3

L – Low Demand Variation
L – Low % of IDIT demand
H – High Fixed Cost
L – Low Holding Cost
3 – Facility grouping

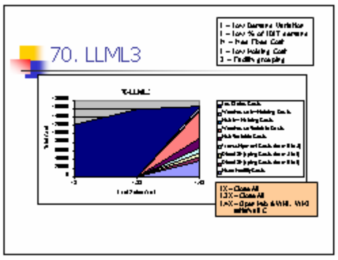
1X – Close All
1.4X – Close All
1.5X – Open Hub & WH1. WH1 within all C



69. LLMH3

L – Low Demand Variation
L – Low % of IDIT demand
M – Med Fixed Cost
H – High Holding Cost
3 – Facility grouping

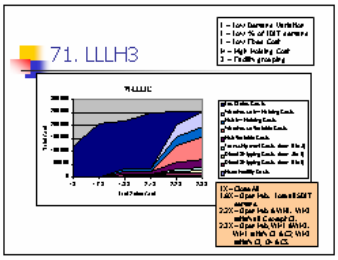
1X – Close All
2X – Close All
2.1X – Open Hub & WH1. WH1 within all C



70. LLML3

L – Low Demand Variation
L – Low % of IDIT demand
M – Med Fixed Cost
L – Low Holding Cost
3 – Facility grouping

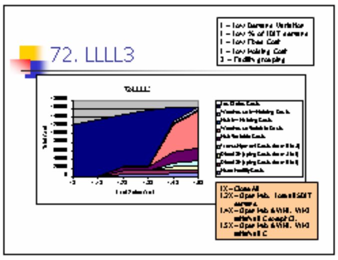
1X – Close All
1.3X – Close All
1.4X – Open Hub & WH1. WH1 within all C



71. LLLH3

L – Low Demand Variation
L – Low % of IDIT demand
L – Low Fixed Cost
H – High Holding Cost
3 – Facility grouping

1X – Close All
1.8X – Open Hub. Lose all SDIT demand.
2.2X – Open Hub & WH1. WH1 within all C except C1.
2.3X – Open Hub, WH1 & WH3. WH1 within C1 & C2; WH3 within C3, C4 & C5.

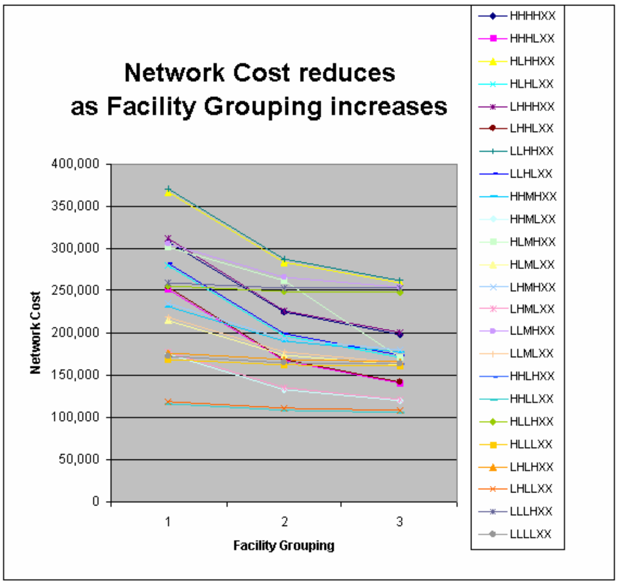


72. LLLL3

L – Low Demand Variation
L – Low % of IDIT demand
L – Low Fixed Cost
L – Low Holding Cost
3 – Facility grouping

1X – Close All
1.2X – Open Hub. Lose all SDIT demand.
1.4X – Open Hub & WH1. WH1 within all C except C1.
1.5X – Open Hub & WH1. WH1 within all C

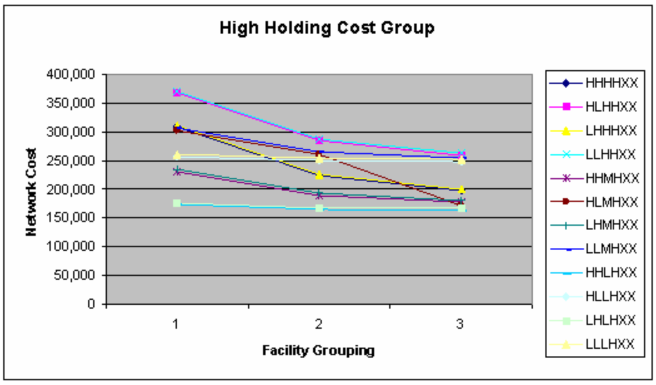
Appendix 5 – Network Cost Reduces as Facility Grouping Increases

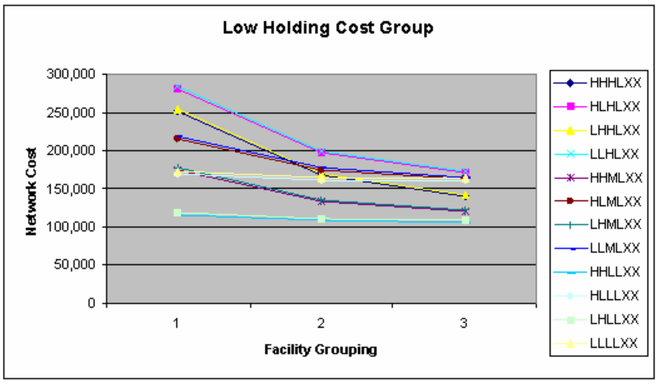


As shown in the graphs above, the network cost reduces as the facility grouping increases. This cost reduction is because more customer locations can be served from the same facility, thus sharing the fixed cost. This reduction is more significant from facility grouping 1 to 2, than from 2 to 3.

One exceptional case occurs for the combination HLMHX inclusive of Runs # 21, 27 and 33 for. In this case, the network cost increases when facility grouping increases from 1 to 2; and decreases when facility grouping increases from 2 to 3.

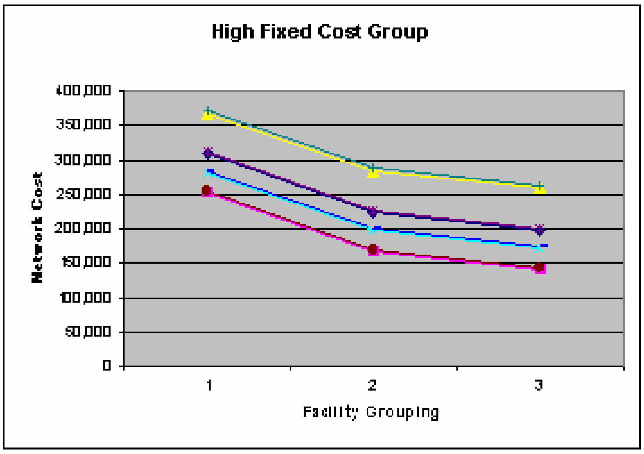
Appendix 6 – Networks with lower holding cost can expect higher % reduction in network cost, with increased facility grouping

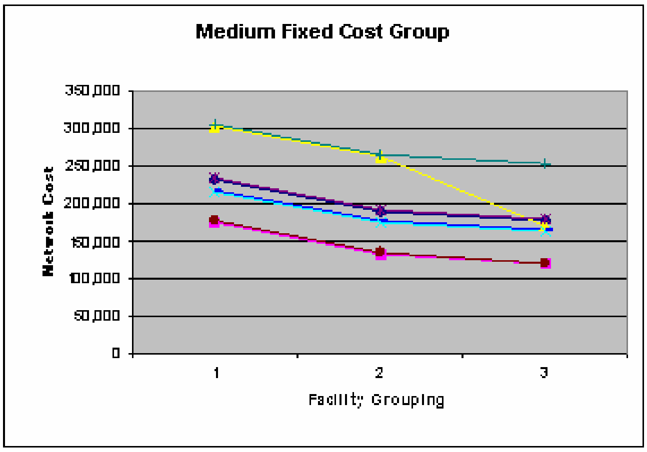


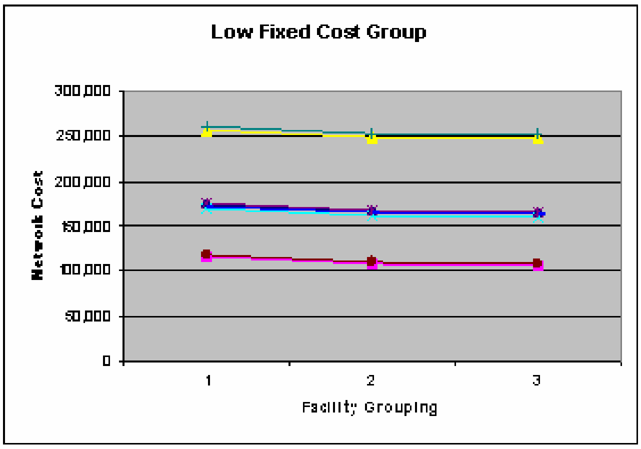


As facility grouping increases, the same facility can serve more customer locations and thus will result in holding more inventories, which takes greater advantage of the lower holding cost.

Appendix 7 – Networks with high facility fixed cost can benefit the most from multiple-facility grouping







Multiple facility grouping allows more demand to share the fixed cost of the facilities involved. This sharing becomes more beneficial when the fixed cost is high.