Warehouse Network Design for A Commodity Chemicals Manufacturer

by

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ABSTRACT

The choice of the location and number of warehouses is a strategic-level decision that can have a long-lasting impact on a firm's performance. Warehouse locations and their capacities determine how products flow within a firm's supply chain, which directly influences a firm's performance in terms of cost and service level. This research applies a mixed integer linear programming method to evaluate factors that drive existing inefficiencies in a warehouse network belonging to a Thai commodity chemicals manufacturer. The objective is to determine an optimal warehouse network configuration that minimizes the firm's total transportation and warehousing cost. Inventory turns and storage capacity constraints are found to be the key drivers of inefficiencies. The optimal solution suggests that the company should retain fewer warehouses and expand capacities at these locations. As the company continues to grow, the potential benefit from expansion becomes greater

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Tables and Figures

1. Introduction

The sponsored company is a petrochemicals firm headquartered in Thailand. The Company manufactures a full range of products ranging from upstream to downstream petrochemicals. A majority of its revenue comes from both domestic and export sales to over 100 countries. The Company has production facilities in Thailand and across various countries in Southeast Asia.

This project focuses on the Company's commodity chemicals businesses in Thailand. Commodity chemicals are typically manufactured in continuous process, large scale chemical plants. They are characterized by low product differentiation and are price-sensitive. Hence, manufacturers of commodity chemicals generally compete on producing at the lowest cost possible. Commodity chemicals are primarily sold in bulk, which means economies of scale is very important. Chemical manufacturing plants are often located in clusters that share utilities, materials, and other facilities to benefit from exchanging resources.

The goal of this project is to analyze the Company's existing warehouse network in Thailand and to determine the best possible warehouse network configuration such that total costs are minimized. Specifically, the research question aims to answer "how many warehouses should the Company have and what should their sizes be to minimize total transportation and warehousing costs?"

2. Motivation

The Company's Thailand operations are concentrated in a petrochemicals industrial estate in an industrial estate east of Bangkok. For its commodity chemicals businesses, the Company is facing inefficiencies in its warehousing operations, particularly from multiple movements of products among its warehouses before the products are shipped to customers. In 2015, these multiple product movements amount to approximately 25% of total transportation cost. The Company's warehouse network has gone through incremental changes in the past, resulting in a network of multiple warehouses located in close proximity. Such a network configuration potentially limits the company from economies of scale as well as adds transportation costs. As a result, the Company would like to explore opportunities to optimize its warehouse network and achieve cost savings from an improved network design.

2.1. Project Background

This project focuses on the commodity chemicals businesses in Thailand. These businesses are operated in a common network which consists of multiple manufacturing locations and warehouses located in the eastern part of Thailand. Multiple production plants are located within a manufacturing location. Each manufacturing location has a warehouse that receives finished products from all production plants at that location. In addition to these plant-attached warehouses, there are also standalone warehouses. These standalone warehouses are also located within 60km of the manufacturing locations.

The Company manufactures all products based on forecasts. Finished goods are received from a production plant to a warehouse before they are shipped to customers. It is possible that a product is moved to more than one warehouse before it is shipped to a customer. For example, a product is received from a plant into a warehouse that is attached to that plant, where it is stored there for a few days. Then, the product may be shipped from the first warehouse to be stored at the second warehouse. Finally, the product is shipped from the second warehouse to a customer. This process is called "internal transfer." Based on a discussion with the Company's logistics manager, the key driver of this internal goods movement is the limited storage space at warehouses that receive products from a production line ("plant-attached warehouses"). As a result, some products will always have to be moved out to another warehouse to make room for incoming finished goods from the production line. Given that petrochemicals production is a continuous process, this internal transfer process happens on a regular basis. In addition to internal transfer movements, there is also high space utilization in the warehouses. Figure 1 shows an average inventory over the past 12 month period. The average inventory exceeded 80% of warehouse storage capacity for 11 out of 12 months, with one month's average inventory exceeding the 100% warehouse storage capacity threshold.

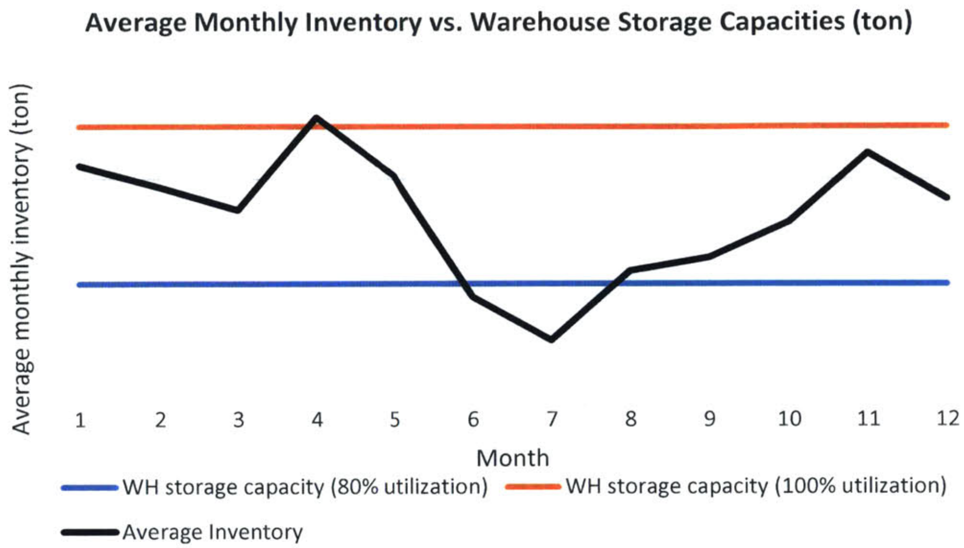

Figure 1 Average monthly inventory compared to warehouse storage capacities over a 12-month period

3. Literature Review

This literature review was conducted to identify appropriate modelling techniques including objectives, parameters, and constraints for designing an optimized supply chain network, with a particular focus on warehouse network. This section will begin by discussing the benefits of supply chain network design in general followed by details of modelling methods specific to warehouse problems.

3.1. Supply Chain Network Design

A supply chain network design involves making strategic level decisions that have a long-lasting effect on the firm (Simchi-Levi, Kaminsky, & Simchi-Levi, 2003). These include decisions about the optimal number, locations, and capacities of warehouses and production plants, as well as determining where products should be made and how they should flow within the supply chain (Watson, Lewis, Cacioppi, & Jayaraman, 2012). This thesis considers a network design problem in which production plants are assumed to be fixed, and the decisions are to be made regarding warehouses and material flows.

A network design model enables firms to understand and evaluate how factors such as number, location, and customer service requirements affect their operational costs and performances compared to the optimal design configuration (Watson et al., 2012). Traditionally, a network design analysis is triggered when there is a major change to a firm's supply chain such as after mergers and acquisitions. Such analysis has been shown to reduce firms' supply chain costs by 5% to 15% (Watson et al., 2012).

Recent trends show that companies perform a network design more regularly, such as on a quarterly basis, to proactively assess that their supply chain is performing optimally against changes in business environments (Watson et al., 2012).

3.2. Modelling Methods

Different approaches have been used to solve network design problems, depending on the configurations of the network, and the objectives of a network design study. This section aims to discuss methods and problems that are relevant to warehouse network design where production sites are assumed to be fixed, warehouses incur handling and fixed costs subjected to capacity constraints, and the objective is to minimize supply chain costs.

Mixed integer programming (MIP)[1] is widely used to model and optimize a distribution network due to its ability to incorporate key elements of a supply chain problem including decision options, constraints, and objectives, and provide an optimal solution (Shapiro, 2001). In fact, a distribution center (DC) location problem is a classic application of MIP (Shapiro, 2001). In this problem, the objective is to redesign a network of DCs such that transportation and warehousing costs are minimized without degrading service level. While traditional models often involve finding an optimal location for a new warehouse, Melachrinoudis and Min (2007) shows that network design can also be used to determine which warehouses to close and consolidate in existing locations. In their MIP model, Melachrinoudis and Min (2007) incorporate transportation, warehousing, and relocation costs. The model assumes fixed demands and capacities; however, sensitivity analyses were also performed on the optimal solution to test effects of policy changes.

A key drawback of MIP is that it can require a long computational time especially when solving large problems. Hence, an approximation method can be used to solve complex optimization problems. Jayaraman (1998) proposes a Lagrangian relaxation method[2] to solve an optimization problem involving capacitated warehouses and multiple products. The model recommends the number and location of warehouses based on differentiated distribution strategies among products and customers, while minimizing warehousing and transportation costs.

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[1] Mixed integer programming model is a type of linear programming model which consists of both integer and continuous variables (Shapiro, 2001).

[2] Lagrangian relaxation is a method in an optimization problem in which constraints that are difficult to solve are put in the objective function, and are assigned penalty (weight) when a solution does not satisfy the constraint (Fisher, 1985).

In contrast to Jayaraman's model, Watson et al. suggest that, although every facility in real-life has a limited capacity, it is sometimes a better practice not to include capacity in an optimization model except for a special reason, such as the need to comply to regulations. Watson et al. provide three main reasons for excluding capacity. First, the optimization model will attempt to distribute demand across facilities to minimize average distance. Second, warehouse capacity can usually be added inexpensively. Third, since the purpose of a network design is also to consider changes in the future, capacity should not be fixed. Hence, it is preferable to have the model dictate the optimal size of a facility.

Cost parameters are incorporated into an optimization model to evaluate financial benefits of the optimal solution over the existing situation. Transportation is arguably the most important cost in network design study (Watson et al., 2012). This is because a change in location and number of facilities will influence transportation costs much more than other costs. Transportation costs should be expressed in cost per unit of demand, not shipment (Watson et al., 2012). For facilities, fixed costs and variable costs can be incorporated. Variable cost can be easily estimated as it is directly proportional to the amount of materials that flow through a warehouse (a warehouse's throughput). In contrast, fixed cost is more difficult to estimate because it is not directly proportional to a warehouse's throughput. Warehouse fixed cost typically varies with the warehouse space capacity in a non-linear fashion.

To overcome the difficulty of estimating the fixed cost, Simchi-Levi et al. (2003) suggest using inventory turnover ratio to estimate a warehouse space, and subsequently a warehouse fixed cost. An inventory turnover ratio is defined as annual sales divided by the average inventory level. Given an inventory turnover ratio and annual sales, average inventory level can be determined. Since the amount of warehouse space needs to support peak inventory, not just average inventory level, the amount of space required can be estimated by multiplying the average inventory level by a factor. In general, peak inventory is twice the amount of the average inventory level. Simchi-Levi et al. (2003), however, suggests that a factor of three is typically used, since in reality a warehouse needs to have extra space for processing and operations. The factor, however, is based on the specific technology used at a warehouse, and should be assessed for a specific network design problem.

While variable and fixed costs are typically defined as previously described, there is no hard rule on what costs are fixed or variable. The more important point is that they should be included in a model in such a way that supports the model's objective (Watson et al., 2012). For example, Melachrinoudis and Min (2007) separate costs further into three types: fixed, capacity, and variable costs. In some network design models, the inventory holding costs should also be included if the costs account for more than 5% of total supply chain costs (Shapiro, 2001). Shapiro further describes different methods to include these costs into the model.

As described earlier, a network design problem involves making a trade-off among conflicting factors, the most typical pair being cost and service level. However, problems in the real world often involve multiple trade-offs which can be both qualitative and quantitative. Several methods can be used to incorporate them into an MIP model. A standard approach is to perform sensitivity analyses by parameterizing key inputs (Daskin, 1995). Korpela and Lehmusvaara (1999) show that the Analytical Hierarchy Process (AHP) can be used to incorporate and systematically quantify qualitative factors. In their model, customer service criteria are quantified and used as inputs into the MIP model that maximizes overall customer satisfaction within capacity constraints.

4. Methodology

Building on the methods discussed in the previous section, this section describes the detailed design of the optimization model to achieve the objective of this project, which is to determine the optimal warehouse network configuration. An overall design for the model is first described, followed by a detailed discussion of all the necessary input data and their assumptions.

4.1. Model Design

The goal of this project is to analyze the total transportation and warehousing costs incurred to the Company from operating the current warehouse network, and to determine what would be the best possible warehouse network configuration such that total costs are minimized. Given this objective to understand and optimize the network based on costs and constraints, MIP can be appropriately used to model our problem of interest. Specifically, the model is intended to address the following questions:

1. What is the total cost of the Company's current warehouse network?
2. Which warehouses should be retained, expanded, and eliminated such that the total cost is minimized?
3. Which customers should be served by which warehouses?

The model has a single objective, which is to minimize the total cost of transportation and warehousing. This objective is in line with the goal to reduce unnecessary transportation costs and gain economies of scale. There are three sets of nodes in the network configuration: origin, intermediate, and destination nodes. The origin nodes consist of production sites where finished goods are manufactured and shipped to the next stage. The intermediate nodes are warehouses where finished goods are received from production sites and are shipped to customers. The destination nodes are a set of aggregated customer demand. To capture the internal transfer process, a logical path is added to allow products to flow from a production plant to a warehouse that is not attached to the plant. An example diagram of this network is shown in Figure 2. The cost of internal transfer is then incorporated to these logical paths. This approach helps to simplify the model while allowing costs associated with internal transfer to be captured. In actual operations, it is also possible for a product to move from one standalone warehouse to another standalone warehouse. This movement path, however, is not represented in the model, since it is an exceptional case. By creating and running an optimization model, the objective is to come up with a solution to the supply chain that assumes that there are no exceptions. To address these exceptions, the optimized baseline can then be compared to the actual baseline.

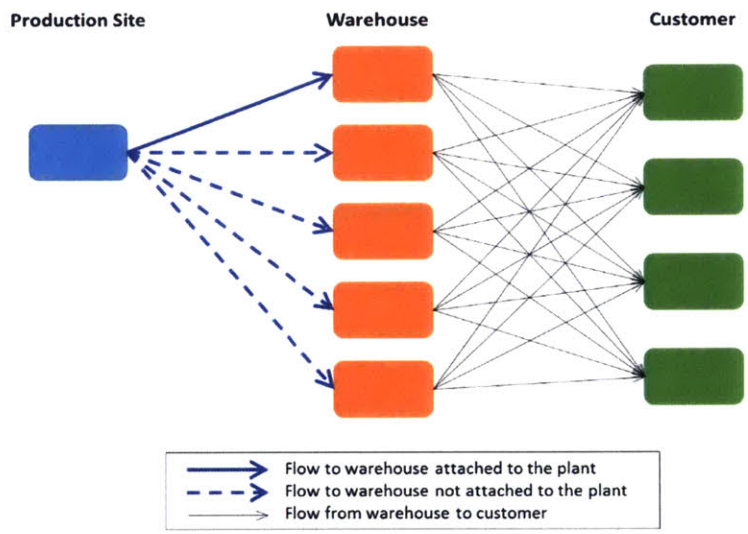


Figure 2 Logical network diagram for the optimization model

4.2. Model Inputs

The following data were collected, aggregated, and incorporated into the model as cost and constraint parameters:

- Product data
- Annual demand by customer location
- Production plant data
- Transportation costs
- Warehousing costs and capacities

4.2.1. Product Data

In this model, all SKUs are grouped into one product with base units, tons. There are two reasons for this aggregation. First, all SKUs are plastic pellets that are different in their chemical properties, not physical properties. While the products come in a few different package types, they can be stored in the same storage area. Therefore, from a logistics point of view, they are identical. Second, the Company uses the base unit, ton, as the basis in supply chain planning activities including sales, inventory, production, and distribution planning. Therefore, it is reasonable to aggregate and represent the flow of materials in this base unit.

4.2.2. Annual Demand by Customer Location

Annual customer demands are aggregated into four demand points, three of which belong to domestic customers, and one that belongs to export customers, as shown in Table 1. Domestic customers' locations are divided into three zones based on delivery time. Export customer demands are clustered into one demand point because all of the Company's export shipments are shipped to international customers via Laemchabang port. The aggregated customer demands for each group are obtained from the Company's historical shipment data.

Table 1 Aggregated customer demand

Customer group	Representative location	Delivery time (day)
Group 1	Bangkok	1
Group 2	Rayong	0.5
Group 3	Nakornratchasima	2
Group 4	Laemchabang	-

4.2.3. Production Plant Data

The Company provided historical production volume for each production site. In this model, it is assumed that the choice of production site to satisfy the demand of a specific customer group can be pre-determined. For example, it is possible to specify that a certain percentage of production output from plant P1 will be used to satisfy demand of group 1 customers. This assumption is reasonable based on the fact that each production site produces a specific set of product categories based on the technologies employed at the plants. Hence, it is possible to allocate customer demand back to a plant source based on projected sales in each product category. Unless there is a major change in product mix (driven by changes in technology), this demand allocation is unlikely to change much across customer groups. Based on production volume in 2015, demand allocation from each customer group to a plant can be summarized as shown in Table 2.

Table 2 Allocation of customer demand to production plant (%)

Customer allocation	Plant 1	Plant 3	Plant 7
Group 1	32	21	33
Group 2	6	4	6
Group 3	5	3	5
Group 4	57	72	56
Total	**100**	**100**	**100**

4.2.4. Transportation Cost

Transportation cost can be separated into inbound and outbound costs. The inbound transport cost is the cost to move one unit of product from a production plant to a warehouse. The outbound transportation cost is the cost to move one unit of product from a warehouse to a customer. For inbound transportation, the average cost between each production plant and warehouse is used. An average is a reasonable estimate because products are always moved in full truck loads using one type of truck. For a product that is moved from a production site to a warehouse attached to it, the inbound cost is assumed to be zero. An average inbound cost from any production plant to all warehouses except Laemchabang warehouse is the same because they are located very close to each other. Similarly, an average inbound cost from any production plant to a Laemchabang warehouse is the same due to close proximity among the production plants.

For outbound transportation cost, an average transportation cost between each warehouse to each customer location is used. This simplification is possible because all orders are shipped in full truck loads for domestic orders and in full container loads for export orders. Additionally, over 80% of domestic orders are shipped using one truck type.

The model assumes that the Company is responsible for all domestic shipments to customers. In reality some of the domestic shipments are sold under ex-factory incoterm, where customers come pick up products at the Company's warehouses. In 2015, this number is approximately 14% of total domestic sales volume. This assumption about domestic shipments is, however, valid and appropriate for our purpose because a network should be designed based on locations which drive transportation costs, not on commercial terms that can vary over time.

4.2.5. Warehousing Costs and Capacities

The Company provided warehouse capacities and costs. Cost data is obtained from the Company's ERP system. Capacities are estimated based on current resources. A warehouse's throughput capacity is calculated from the number of trucks that each warehouse could handle per day, multiplied by the number of units that can fit on a truck and the number of working days in a year. Warehouse fixed and variable costs are obtained from the Company's ERP system.

A warehouse's storage capacity in base units, tons, is provided by the Company. This is the storage capacity at 80% utilization, which is the maximum utilization at which a warehouse can operate efficiently. To take into account variability across months, inventory turnover ratio for company-owned warehouses is calculated into three numbers based on the Company's historical days of sales data in 2015. For modelling purposes in the baseline scenario, 20, 25, and 30 days of sales are used to represent maximum, mean, and minimum inventory turnover, respectively. For one of the standalone warehouses operated by a 3PL, a historical inventory turnover ratio of 32 is used. The 3PL's warehouse holds approximately half the amount of inventory in terms of days of sales compared to the Company's own warehouse. This reflects the current policy that products should be moved to warehouse WL to fulfill customer orders within the first 3-7 days. Hence, inventory at 3PL's warehouse moves at a faster rate than that of the Company's own warehouses. Table 3 summarizes the inventory turnover ratios used in the model.

Table 3 Inventory turnover ratios for different average inventory levels

Average inventory levels	All warehouses except WL	WL
Minimum	18.3	32
Average	14.6	32
Maximum	12.2	32

In this model, inventory holding cost is not considered although inventory typically represents a large portion of costs in petrochemicals supply chain. The reason is in our problem setting, inventory stored in different warehouse locations does not have an effect on service level to customers.

4.3. Model Formulation

In this section, the problem in question is formulated into a mathematical model that takes in data aggregated as described in the previous section as inputs, and optimizes for the best possible network configuration based on the model's objective.

4.3.1. Model Objective

The goal of this project is to reconfigure the Company's warehouse network such that total cost is minimized. Therefore, the objective function of the model is to minimize the sum of transportation and warehousing costs. This objective is aligned with the characteristics of the product, which is a commodity that competes on low cost.

4.3.2. Model Parameters

The following parameters have been created to be incorporated into the model based on the model inputs described in section 4.2.

- P_i = Production site i, where $i \in \{1, 3, 7\}$. There are three production sites: P1, P3, and P7.
- W_j = Warehouse j, where $j \in \{1, 3, 7, 10, L\}$. There are five warehouse locations: W1, W3, W7, W10, and WL.

  For a warehouse that is attached to a production site, its index corresponds to the production site's index. For example, warehouse W1 is located within the production site P1. A warehouse without a corresponding production site is a stand-alone warehouse.
- G_k = Customer k, where $k \in \{1, 2, 3, 4\}$. There are four customer aggregates.
- C_{ij} = Cost of transport one unit of product from production site i to warehouse j. Unit is baht/ton.
- C_{jk} = Cost of transport one unit of product from warehouse j to customer k. Unit is baht/ton.
- HI_j = Handling cost to process internal transfer at warehouse j. Unit is baht/ton.
- HC_j = Handling cost to process customer shipment at warehouse j. Unit is baht/ton.
- F_j = Fixed cost of warehouse j. Unit is baht/year.
- D_{ik} = Demand of customer k that is fulfilled by production site i. Unit is ton/year.
- $TCap_j$ = Throughput capacity of warehouse j. Unit is ton/year.
- $SCap_j$ = Storage capacity of warehouse j. Unit is ton.
- T_j = Inventory turnover at warehouse j. Unit is times/year.
- M = An arbitrary large number

4.3.3. Decision Variables

Based on the problem of interest, two decisions should be made by the model. First, which customer is serviced by which warehouse from which production plant? Second, should a warehouse be opened, and if so, what should be its capacity? These decisions are defined by the following variables:

- X_{ijk} = Volume of products assigned to customer k shipped from production site i to warehouse j. Unit is ton/year.
- Y_{jk} = Volume of products shipped from warehouse j to customer k. Unit is ton/year.
- Z_j = Binary variable which equals to 1 if a warehouse j is open, and 0 otherwise.

4.3.4. Mathematical Formulation

$$Minimize\ \sum_k \sum_j \sum_i X_{ijk} C_{ij} + \sum_k \sum_j Y_{jk} C_{jk} + \sum_k \sum_j \sum_i X_{ijk} HI_j + \sum_k \sum_j Y_{jk} HC_j + \sum_j F_j Z_j$$

for all i, j, k where i ∈ {1, 3, 7}, j ∈ {1, 3, 7, 10, L}, and k ∈ {1, 2, 3, 4}. (1)

Subject To:

- Flow balance

$$\sum_{i,k} X_{ijk} = \sum_k Y_{jk} \quad for\ each\ j \qquad (2)$$

- Demand satisfaction

$$\sum_j Y_{jk} = \sum_i D_{ik} \quad for\ each\ k \qquad (3)$$

- Throughput capacity constraint

$$\sum_k Y_{jk} \leq TCap_j \quad for\ each\ j \qquad (4)$$

- Storage capacity constraint

$$\sum_k Y_{jk} \leq SCap_j \times T_j \quad for\ each\ j \qquad (5)$$

- Linking constraint & non-negativity

$$\sum_k Y_{jk} \leq Z_j M \quad for\ each\ j \qquad (6)$$

$$Z_j = 0, 1 \qquad (7)$$

$$X_{ijk}, Y_{jk} \geq 0 \qquad (8)$$

The objective function (1) is to minimize the total cost of transportation and warehousing. Constraint (2) ensures that the flow of products coming into a warehouse is equal to the flow of products going out of a warehouse. Constraint (3) forces the model to always meet demand. Constraints (4) and (5) ensure that the throughput and storage capacity at a warehouse cannot be exceeded, respectively. Storage capacity constraint is represented in the model by converting into the amount of flow that the storage capacity can support. The rationale is that the amount of flow that a certain storage capacity can support depends on the inventory turnover. Given a fixed storage capacity, the higher the inventory turnover, the higher the flow volume. Constraint (6) dictates that if a there is a flow through a warehouse, then the warehouse must be opened. Constraint (7) is a binary variable that takes a value of 1 if a warehouse is opened and 0 otherwise. Finally, constraint (8) forces the volume of products to be a positive number.

5. Results

Based on the model formulated previously, this section describes results of model validation and optimization runs for different network configuration scenarios.

5.1. Model Validation

To test that the model accurately represents the network design problem in question, actual shipment data in 2015 were used to validate the model. The output suggested by the model is then compared to actual costs incurred by the Company. Figure 3 shows validation results for each cost components.

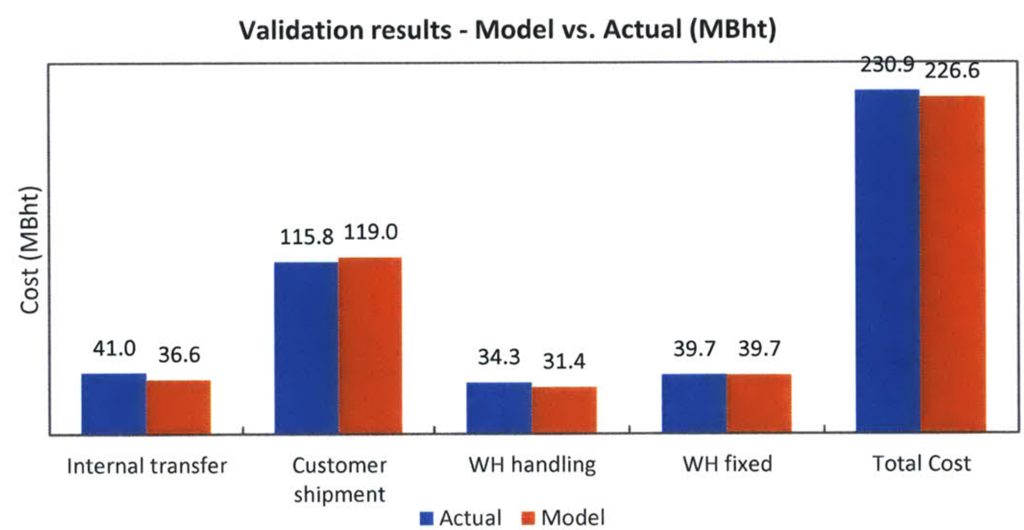


Figure 3 Model validation results

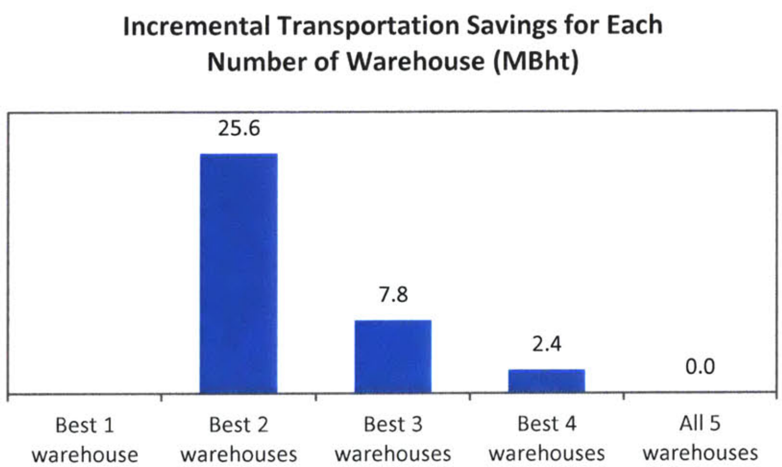
Overall, the model underestimates the total cost by about 2%. In particular, internal transfer and warehouse handling costs are underestimated by 10% and 8%, respectively. This is because the model only considers costs associated with movements that generate sales volume. In contrast, the Company's accounting data contains both costs associated with movements that generate sales volume and those that do not. For example, when a product is moved from one warehouse to another and has not been sold, its internal transfer and handling costs would already be recorded in the accounting system, but are not represented in the model. Using the Company's accounting data, it is not possible to distinguish between the two costs.

5.2. Model Results

This section analyzes the results of the optimization program in different scenarios. First, a simple model considering only transportation cost is used to understand implications of different warehouse locations in the network. Then, a model which incorporates warehousing cost and capacities is used to assess different scenarios. Finally, optimization results are presented in terms of associated costs and capacities.

5.2.1. Optimized model on transportation costs only

In this model, only transportation costs are incorporated into the model, and the objective is to minimize the total cost. The purpose is to assess the incremental value of opening each additional warehouse in terms of transportation cost savings. Five scenarios have been tested. In each, a different number of warehouse is allowed to be opened. The total cost and details associated with each scenario are shown in in Figure 4.



Scenario	Warehouses selected
Best 1 warehouse	WL
Best 2 warehouses	WL, W7
Best 3 warehouses	WL, W7, W1
Best 4 warehouses	WL, W7, W1, W3
All 5 warehouses	WL, W7, W1, W3 (W10 not selected)

Figure 4 Incremental transportation savings for each number of warehouse based on a simple model with transportation cost only

When one warehouse is allowed to open, the model selects WL. If two warehouses are allowed to be open, the model selects WL and W7. Having this second warehouse will save approximately 25.6 MBht in transportation cost. Based on this result, it can be argued that the cost of operating the second warehouse should not exceed this amount. The incremental savings from adding the third and fourth warehouses are approximately 7.8 MBht and 2.4 MBht, respectively. The incremental savings for adding the third and fourth warehouses diminish greatly since their locations are very close to the two warehouses that have already been selected. This result shows that there is little gain from transportation cost savings by adding these warehouses. In the last scenario when all five warehouses are allowed to open, warehouse W10 is not selected. This result, again, suggests that given such close proximity among the warehouses, the maximum number of warehouses that the Company should have in its existing network is four at locations W1, W3, W7, and WL. Warehouse W10 location presents no additional value in terms of transportation cost savings.

5.2.2. Optimized model with transportation and warehousing costs and capacities

This section presents results from the optimization runs of the baseline model which incorporates transportation, warehousing costs, and capacity constraints. First, the model only considers the warehouses in the Company's existing network. Nine optimization runs are performed to understand key influencing factors and total cost of the existing network under different scenarios. Then, the model is expanded to consider options to expand existing warehouses. Finally, the total costs across all the scenarios are compared and summarized in Figure 5.

Scenario 1: Baseline scenario with average inventory turns

In this scenario, the warehouse storage capacity is set to 80% utilization. Inventory turns are set at 14.6 for all warehouses except WL, which is set at 32. Four warehouses–W1, W3, W7, and WL–are selected. Warehouse space is fully utilized at W1, W3, and W7, while WL storage space is nearly fully utilized at 97%. Throughput capacity, on the other hand, is less than 50% utilized in warehouses W1 and W7. At WL, 83% of throughput capacity is utilized.

Scenario 2: Baseline scenario with maximum inventory turns

In this scenario, the warehouse storage capacity is set to 80% utilization. Inventory turns are set at 18.3 for all warehouses except WL, which is set at 32. Only three warehouses–W3, W7, and WL–are selected. Warehouse space is fully utilized at W3 and W7, while WL space is nearly fully utilized at 96% of the effective capacity (assuming 80% utilization). Throughput capacities of W3 and W7 increase to 67% and 43%, respectively.

Given the higher inventory turnover, the model only needs to use three warehouses. Products originally assigned to warehouse W1 in the previous scenario are now assigned to warehouse WL, except for those shipped to customer group 2. The result suggests that higher inventory turnover causes each warehouse to be able to handle more throughput volume, it become more cost effective to open fewer warehouses and transfer products internally. In this scenario, the decrease in warehouse fixed cost outweighs the increased cost of internal transfer.

Scenario 3: Baseline scenario with minimum inventory turns

In this scenario, the warehouse storage capacity is set to 80% utilization. Inventory turns are set at 12.2 for all warehouses except WL, which is set at 32. Four warehouses–W3, W7, W10, and WL–are selected. Warehouse space is fully utilized at W3, W7, and WL, while it is 60% at W10. Throughput capacity, on the other hand, is less than 50% across all plant-attached warehouses, and is only 27% at W10. At WL, 86% of throughput capacity is utilized.

When inventory turns are low, warehouse W1 is not selected although it is the cheapest warehouse to ship product from P1 because of limited storage capacity at W1. At this level of inventory turnover, the storage space capacity at W1 is capped at 122,000 ton. If W1 was selected instead of W10, there would not be enough capacity to handle the total demand. Therefore, W10, albeit being a higher cost option, is selected instead of W1 for its higher capacity.

Scenario 4: Demand increases by 10% with average inventory turns

In this scenario, demand increases 10% across the board. The warehouse storage capacity is set to 80% utilization. Inventory turns are set at 14.6 for all warehouses except WL, which is set at 32.

When demand increases by 10%, the model selects the same four warehouses as in scenario 3 where inventory turns are at the minimum. In this scenario, storage capacity is fully utilized at W3, W7, and WL, and it is 72% utilized in W10. This result suggests that even when inventory turns are not at the minimum, an increase in demand also leads to the model choosing a higher cost warehouse, W10, over a lower cost warehouse, W1, because the latter will not provide enough capacity to handle the increased volume. Additionally, this suggests a clear capacity constraint at warehouse W1.

Scenario 5: Demand increases by 10% with maximum inventory turnover

In this scenario, demand increases by 10% across the board. The warehouse storage capacity is set to 80% utilization. Inventory turns are set at 18.3 for all warehouses except WL, which is set at 32. The model opens four warehouses–W1, W3, W7, and WL. Compared to scenario 2 with maximum inventory turns, W1 is now open to support the increased volume. Storage capacity is fully utilized across all open warehouses, except at WL, whose utilization is 97% (of the capped 80% utilization).

Scenario 6: Demand increases by 10% with minimum inventory turns

In this scenario, demand increases 10% across the board. The warehouse storage capacity is set to 80% utilization. Inventory turns are set at 12.2 for all warehouses except WL, which is set at 32.

In this scenario, all five warehouses are selected. All warehouses are fully utilized except at W10, where utilization is 81%.

Scenario 7: Baseline scenario with transportation costs only

In this scenario, the warehouse storage capacity is set to 80% utilization. Inventory turns are set at 14.6 for all warehouses except WL, which is set at 32. Without warehousing fixed and variable costs, warehouse selection is determined based solely on transportation costs and capacities.

Four warehouses–W1, W3, W7, and WL–are selected. This result is consistent with the result in a simple model with transportation costs only in section 5.2.1. Warehouse space is fully utilized at W1, W7, and WL, while it is 88% utilized at W3.

In this scenario, the model selects the same set of warehouses as in scenario 1 where warehousing fixed and handling costs are also included. However, the difference is that in this scenario, warehouse WL is utilized fully instead of W3 which is utilized fully in scenario 1. This suggests that while WL provides more cost savings benefit in terms of transportation cost based on its location, W3 provides more benefit in terms of lower fixed cost. Hence, when all costs are taken into account, W3 is considered a lower cost warehouse compared to WL.

All demand of export customers are assigned solely to WL, suggesting that transportation costs from WL to export customers is the most favorable. The remaining capacity at WL is used to process shipments for domestic customers.

<u>Scenarios 8, 9, 10: Expansion scenarios with average, maximum, and minimum inventory turns</u>

In order to determine whether a warehouse's capacity should be expanded and if so, by how much, the same model from the baseline scenario is run but the capacity constraints are removed. Without capacity limitation, the optimization model is allowed to dictate the optimal capacity such that total cost is minimized.

In this scenario, the same demand as in scenario 1 is assumed. Inventory turns are set at 14.6 for all warehouses except WL, which is set at 32. The optimized model selects only three plant-attached warehouses–W1, W3, and W7. Each warehouse receives and ships out products from its respective plant, therefore, internal transfer becomes zero.

The model is then optimized with minimum inventory turns (12.2) and maximum inventory turns (18.3). The models select the same choice of warehouses, which are W1, W3, and W7. Similarly, each warehouse receives and ships out product from its respective plant making internal transfer zero. The differences among these three optimization runs are the expanded storage capacities dictated by different inventory turns. Here, the expanded storage capacity is calculated by multiplying the average inventory at each warehouse by a factor of 1.25.

Table 4 summarizes the storage capacities dictated by the optimized model.

Table 4 Expanded Storage Capacities for Different Inventory Turns

Scenario	Expanded Storage Capacity (ton)		
	W1	W3	W7

7. Expansion with average inventory turns	62,478	30,208	74,435
8. Expansion with maximum inventory turns	49,981	24,166	59,548
9. Expansion with minimum inventory turns	74,973	36,250	89,321

Figure 5 and Figure 6 summarize total costs and relative cost savings of each optimized scenario compared to the actual baseline.

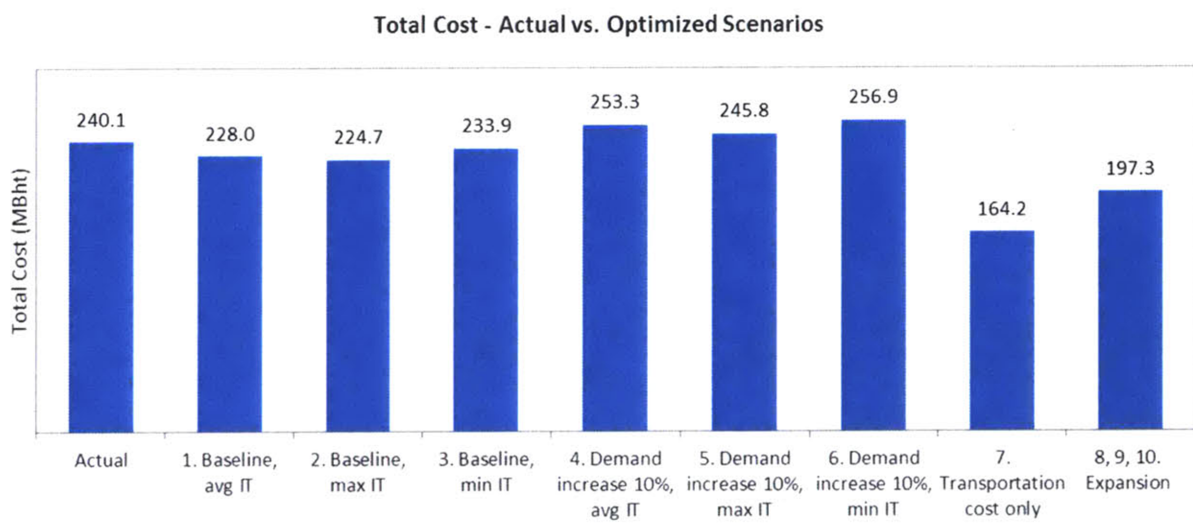


Figure 5 Total cost – Actual vs. Optimized scenarios

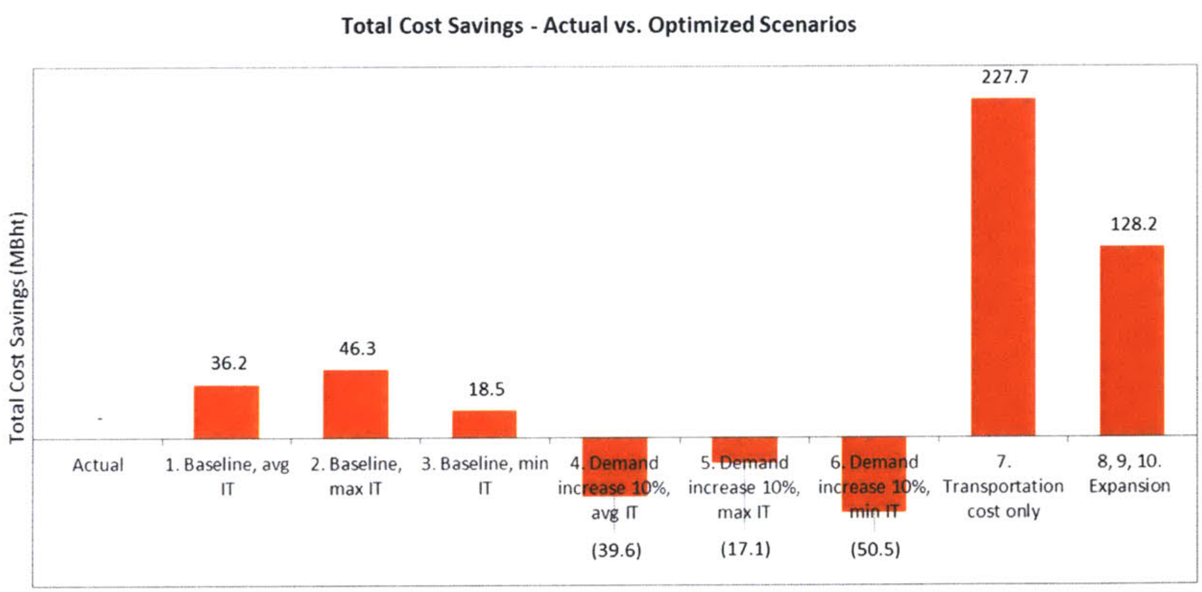


Figure 6 Total cost savings - Actual vs. Optimized scenarios

In additional to total costs, the resulting warehouse throughput and storage capacities for each optimized scenario are presented in Table 5

Table 5 Resulting warehouse throughput and storage capacities for optimized scenarios

Scenario	Throughput Capacity					Storage Capacity				
	W1	W3	W7	W10	WL	W1	W3	W7	W10	WL
1. Baseline, avg IT	23%	53%	36%	0%	83%	100%	100%	100%	0%	97%
2. Baseline, max IT	0%	67%	45%	0%	82%	0%	100%	100%	0%	96%
3. Baseline, min IT	0%	44%	30%	27%	86%	0%	100%	100%	60%	100%
4. Demand increase 10%, avg IT	0%	53%	36%	38%	86%	0%	100%	100%	72%	100%
1. Demand increase 10%, max IT	29%	67%	45%	0%	83%	100%	100%	100%	0%	97%
6. Demand increase 10%, min IT	19%	44%	30%	36%	86%	100%	100%	100%	81%	100%
7. Transportation cost only	23%	47%	36%	0%	86%	100%	88%	100%	0%	100%

5.2.3. Effect of inventory turns on total cost and warehouse choice

Results in the previous section show that warehouse choice and total cost are dependent on inventory turns. For example, in scenarios 1, 2, and 3, different warehouse numbers and choices are selected as inventory turns vary while all else remain constant. To gain a better understanding of this relationship, optimization runs of the baseline model were performed. The result is shown in Figure 7.

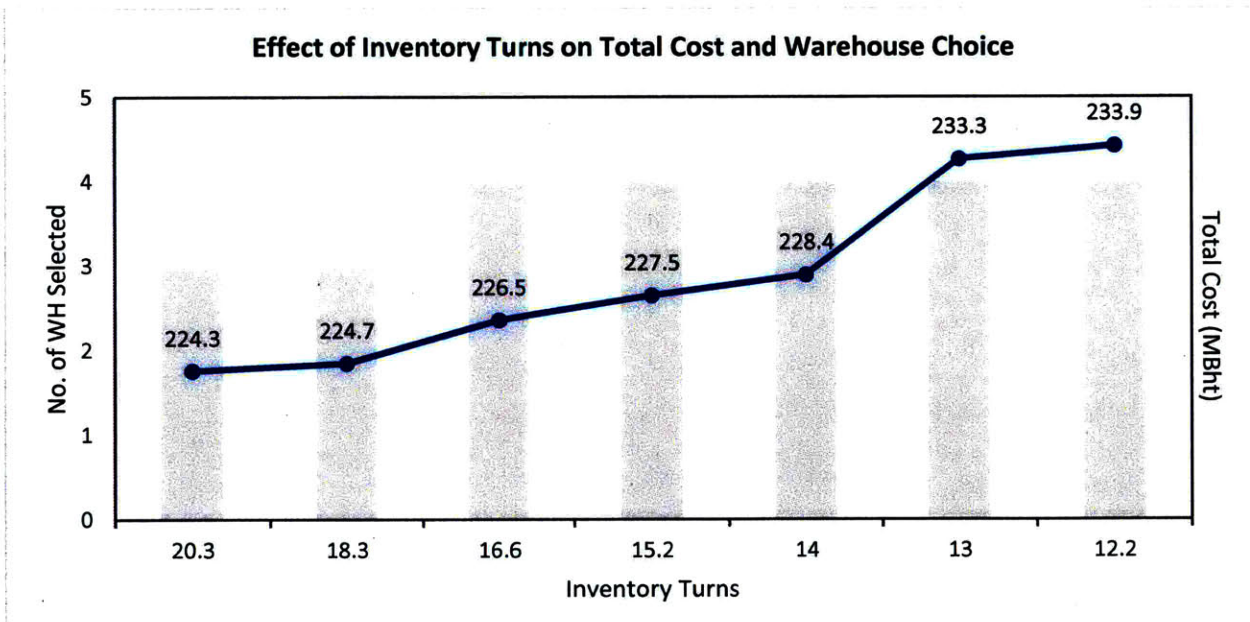


Figure 7 Effect of inventory turns on total cost and warehouse choice

When inventory turns are lower than 18.3, which is still more than the Company's current average of 14.6, four warehouses are open. When inventory turns are 16.6 and below, four warehouses are still sufficient. However, total cost jumps by about 5 MBht/year when inventory turns are less than 13.0. This is because at this rate, the higher cost warehouse W10 is selected instead of warehouse W1. The selection of this standalone warehouse over a plant-attached warehouse results in increased internal transfer, fixed and handling costs.

6. Recommendations

The Company's existing warehouse network is sufficient for the current operations, but it is not optimized. In this section, key findings based on the optimization results in the previous section are first summarized, followed by the suggested warehouse network for the Company.

6.1. Key Findings

- **Limited storage capacity especially at Warehouse 1**

Section 5.2.3 shows that all else being equal, different inventory turns lead to a different optimal configuration. As inventory turns vary, warehouses W3, W7, and WL are always selected. Warehouse W1, however, is not selected when the inventory turns are at minimum, suggesting that its capacity is so limited that having it opened would not allow all demand to be handled. On the other hand, it is also not selected when the inventory turns are at the maximum. In this case, its fixed cost becomes more expensive than the internal transfer cost of moving products from plant P1 to the other warehouses. This is not surprising as warehouse W1 is attached to a production plant that produces nearly 40% of total volume, but it has the least amount of storage capacity among all five warehouses.

- **Storage capacity is the key constraint**

As summarized in Table 5, storage capacity is either fully or nearly fully utilized, while throughput capacity is generally less than 50% utilized in all warehouses except WL, where is around 80% utilized. This suggests that storage capacity is the key constraint and driver of internal transfer cost. However, even without limit on storage capacity, the current throughput capacity at each plant-attached warehouse is also currently less than the production volume that comes from its respective plant. This suggests that the Company should first consider, expanding its storage capacity, and then the throughput capacity.

6.2. Suggested Warehouse Network

Based on the results in section 5.2, the Company can still operate with its existing warehouse network. However, all warehouse will have to remain open and operate at or near capacity. In addition, internal transfer still accounts for 17% of total transportation costs under the optimized scenarios. The most optimal configuration for the Company is to expand three plant-attached warehouses–W1, W3, and W7–and close two standalone warehouses, W10 and WL. In this configuration, all customer orders would be shipped from each warehouse directly to the customers, hence, internal transfer cost is zero. As shown in Figure 8, the difference in total cost between this scenario (198 MBht) and the optimized baseline scenario 1 (228 MBht) is approximately 30 MBht. This difference suggests a threshold for the investment required to expand capacities at warehouses W1, W3, and W7. To test the robustness of the suggested network configuration, a sensitivity analysis is performed in the next section.

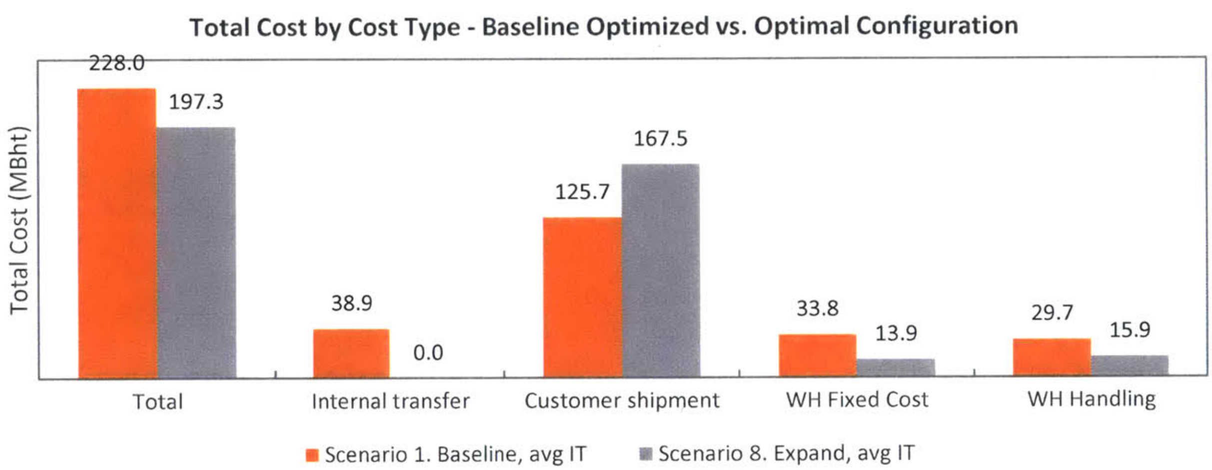


Figure 8 Comparison of total cost - Baseline optimized vs. Expanded configuration

6.2.1. Sensitivity Analysis

A sensitivity analysis is performed on warehouse fixed cost and transportation costs to gain a better knowledge of how changes in these parameters affect the optimal solution. Specifically, it aims to identify the range of values where the optimal configuration remains unchanged.

Warehouse Fixed Cost

First, for each selected warehouse in the optimal network (W1, W3, and W7), its fixed cost is increased until it is no longer selected. Second, for the warehouse not originally selected to be in the optimal network (W10 and WL), its fixed cost is reduced until it is selected. Results are summarized in Figure 9.

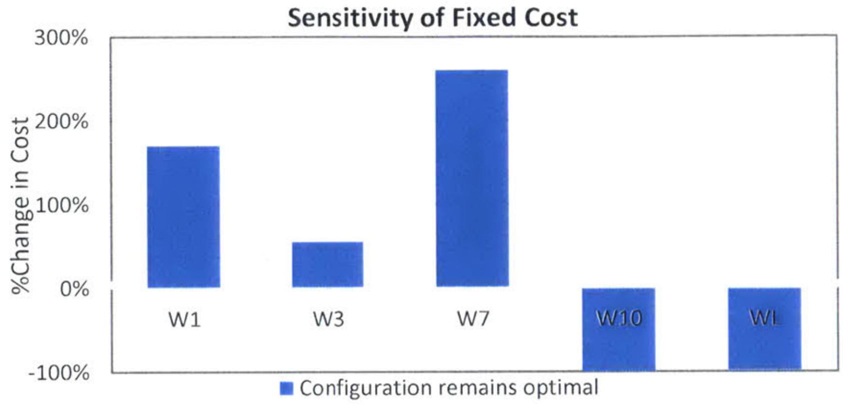


Figure 9 Sensitivity of fixed cost

The fixed cost of warehouse W3 can increase as much as 50% to remain selected. Warehouses W1 and W7 have a much higher threshold at 170% and 260%, respectively. This is not surprising since the majority of production volume come from plants attached to W1 and W7. Therefore, more savings can be gained from not having to move this large volume to the other warehouses. The fixed cost of warehouse WL must reduce by at least 98% for it to be selected. Warehouse W10 remains unselected despite any change to its fixed cost.

<u>Inbound Transportation Cost</u>

In the optimal solution, the total inbound transportation cost is zero since there is no internal transfer. In this sensitivity analysis, the cost of inbound transportation is lowered across the board until the optimal solution change. Results are shown in Figure 10.

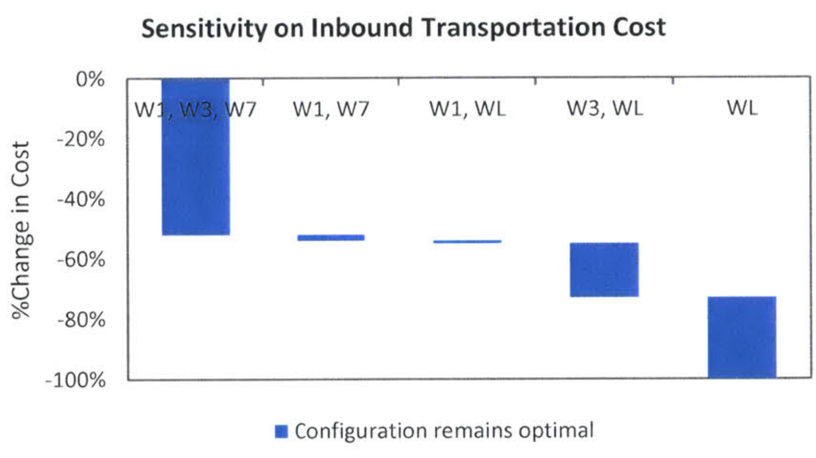


Figure 10 Sensitivity of inbound transportation cost

Once the inbound transportation cost decreases by 51%, W3 is no longer selected and product volume originally goes through this warehouse shifts to W7. As soon as the inbound transportation cost decreases more than 53%, product volume starts to shift more and more towards warehouse WL.

Outbound Transportation Cost

The outbound transportation cost is increased across the board to test its impact on the optimal configuration. Only when the outbound transportation cost increases by more than 58%, the optimal solution change. In this situation, warehouse W3 is closed, and warehouse WL is open to handle volume for customer group 4 (export).

In terms of both inbound and outbound transportation costs, the optimal solution is quite robust since the costs must be reduced by over 50% for the solution to change.

6.3. Suggested Customer to Warehouse Assignment

In the optimal solution, each warehouse receives and ships products directly from its respective plant to customers. Therefore, customer to warehouse assignment is based on which production plant supplies the product needed by the customers.

Nevertheless, the optimized baseline scenarios provide insights into the optimal customer-warehouse assignment in a constrained network. The models suggest results similar to the policy that the Company is currently using, except for warehouse W10. Based on the model's suggestion, the following rules for assigning customer shipments to warehouses can be summarized as follows:

1. Fill up plant-attached warehouses with domestic shipments. If there is any remaining capacity, fill up with export shipments of products coming from their respective plants.
2. Fill up warehouse WL with export shipments. If there is any remaining capacity, fill up with shipments for domestic customers group 1 and 3.
3. Fill up remaining volume to warehouse W10.

7. Discussion

This section discusses the model's limitations and suggests potential improvement.

7.1. Future Improvements

Before fully considering any model implications, additional financial analysis is needed to confirm fixed and variable costs for expansion options, as costs have strong influence on the model results. In addition, costs of closing and opening warehouses should also be considered along with the cost savings benefits from the optimal solutions. Given the exiting network, the Company's key trade-off decision is between warehousing fixed cost vs. internal transfer cost. In contrast to typical network design problems, the outbound transportation cost is less of a concern here since the manufacturing and warehouse locations are close to each other. In case the Company would like to consider a new warehouse location, it should consider an option closer to the customers. As shown in section 5.2.1, warehouse WL is the most favorable in terms of transportation cost, since it is located closer to the customers.

One of the main limitations of the model is that inventory turns are assumed to be the same across all company-owned warehouses. This limitation can be improved in two ways. First, different inventory turns should be used across warehouses based on the products that go through them. Second, the inventory turns should be based on the target turns that the Company would like to achieve, rather than historical data. This is because the value of network design is to provide a network that will support a firm's future operations. In order to determine such targets, the Company may want to perform an inventory analysis exercise to assess their inventory policy, and subsequently, the inventory turns.

The Company may want to run a sensitivity analysis on volume shift among customer groups. The model shows that warehouse WL is favorable for export shipments, but if there is a significant increase in domestic shipment, warehouse WL may not be as desirable as it is now. While the objective of this optimization exercise is to minimize total cost which is appropriate for commodity products, this model could also be expanded to also consider service level for a particular product or customer group.

8. Conclusion

This thesis aimed to analyze the drivers of inefficiencies in the Company's existing warehouse network, and to suggest the optimal network that would minimize total cost. Specifically, it aimed to recommend the optimal warehouse number, and whether existing warehouses should be retained, closed, or expanded.

Optimization results show that the Company should expand its three plant attached warehouses and close all standalone warehouses in order to achieve the highest cost savings by removing all internal transfer. The research effort shows that storage capacity and inventory turns are the main constraints driving the Company's total cost and warehouse choices. In addition, results show that existing warehouse locations are located too close together for the Company to gain substantial cost savings from multiple warehouse locations. As a result, going forward, the Company may want to consider new warehouse locations further away, especially those locations closer to the customers.

While the research effort is able to answer the problem in question, the model can be improved further. Different inventory turns targets can be used for each warehouse. Additionally, more sensitivity analysis can be performed to assess effects of change in volume shift.

The network design study in this thesis will bring both immediate and long-term benefits to the Company. Short-term benefits include insights into factors impacting costs and performance, whose understanding will provide the basis for the Company to pursue cost reduction projects. Over the long term, this network design model can be continually updated and provide a means for making distribution-related decisions to support strategic direction of the Company.

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