Optimizing Tempur Sealy International's North American Distribution Network for the Adjustable Base Category

by

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and

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SUBMITTED TO THE PROGRAM IN SUPPLY CHAIN MANAGEMENT
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF APPLIED SCIENCE IN SUPPLY CHAIN MANAGEMENT
AT THE
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

May, 2024

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Abstract

Rising inventory costs and lower turnover rates, exacerbated by extended lead times and fluctuations in supply and demand, have prompted Tempur Sealy International to reconsider its sourcing, inventory management, and distribution strategies within its adjustable base category. This project developed a mixed integer linear programming model to analyze different distribution configurations, including Direct-to-Distribution Center and Hub-and-Spoke models, and compare sourcing strategies from Asian and nearshore suppliers. We employ a Monte Carlo simulation to evaluate the impact of various strategic decisions on cost. Additionally, we leverage our model to conduct forward-looking supply planning for various scenarios, using demand forecasts for the next year to identify opportunities for near-term cost savings. This capstone project provides Tempur Sealy with actionable insights by quantifying the trade-offs between product, inventory, and transportation costs. Equipped with this information, TSI can improve its decision-making associated with inventory, replenishment, and supplier sourcing decisions.

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1 Introduction

1.1 Motivation

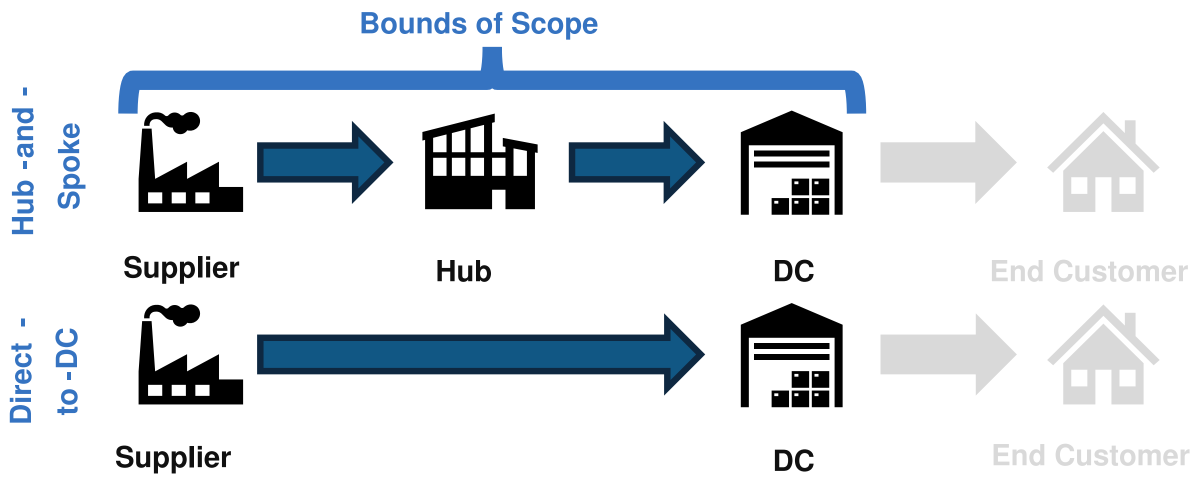
In the intensely competitive and globally interconnected environment of mattress and bedding production, optimizing supply chain networks is pivotal in ensuring cost effectiveness and maintaining a robust service level. Tempur Sealy International(TSI), a prominent player in the industry, navigates through the complex labyrinth of sourcing, deploying, and replenishing its inventory across many product categories. One particularly important category is their adjustable bases. Adjustable bases are foundational components of modern sleep systems that allow users to customize their sleeping positions for enhanced comfort and support. The bases are typically bought as a complementary product to a mattress purchase making it imperative to have the right inventory in the right place at the right time. Traditionally, adjustable bases have been sourced from Asian suppliers and, to a lesser extent, from nearshore suppliers. However, unstable lead times and supplier disruptions, coupled with the volatility and fluctuations associated with customer demand, have increased TSI's costs related to transportation and inventory holding. The rising uncertainty has led to increasing inventory levels to maintain the same customer service level. This project aims to refine TSI's inventory deployment and replenishment strategies, as well as to examine, evaluate, and ultimately enhance the existing design of TSI's supply chain distribution network. To accomplish these objectives, we develop an optimization model to support the design of a distribution network that minimizes total supply chain costs while maintaining a high service level.

1.2 Problem Statement and Research Questions

The dynamics of a global supply chain, especially within the adjustable bases category of TSI's North American operations, present numerous challenges. These include variable supplier lead times and the need to mitigate the risk of supply disruptions while simultaneously maintaining an optimal inventory level. Addressing these challenges requires strategic network design and meticulous inventory management to effectively alleviate risks. TSI aims to minimize total costs, which include product purchasing costs, inventory handling, and holding costs, and both maritime and inland trucking transportation, without compromising their service level.

To achieve this goal, it is necessary to evaluate different supplier sourcing and inventory replenishment strategies to find the most cost-effective and efficient distribution network. Supplier sourcing strategies involve decisions about the mix of production locations, based on factors like product cost, lead times, and transportation costs. Inventory replenishment strategies refer to the distribution models used within TSI's network. Two models are considered: Direct-to-DC and Hub-and-Spoke, represented in Figure 1. The Hub-and-Spoke model features "Hubs" which are large distribution centers tasked with shipping adjustable bases to the "Spokes". The "Spokes" are smaller distribution centers that handle fulfilling orders to end customers. This strategy allows the "Hubs" to act as central warehouses that aggregate inventory, while the "Spokes" support more localized and direct distribution to end customers. The Direct-to-DC model utilizes direct shipping from suppliers to DCs, bypassing the hubs.

Figure 1
Flow paths for Direct-to-DC and Hub-and-Spoke Model.



Given these complexities and strategic imperatives, our project investigates how TSI can optimize its supply chain network to maintain a high service level while optimizing supply chain costs. Our project seeks to address the following topics:

(i) *Scenario Analysis for Supply Chain Network Design Decisions*
How can various distribution and sourcing strategies, including a Direct-to-DC and a Hub-and-Spoke model or an offshore and nearshore sourcing strategy, be analyzed to determine the optimal network design to balance cost and service level? As TSI transitions towards distributing more through a Hub-and-Spoke model, a detailed analysis of their inventory deployment and replenishment strategy becomes essential. Our analysis compares scenarios where products are concentrated at central hubs versus more evenly distributed across spokes. Distributing products closer to end customers aims to reduce delivery times and transportation costs. Furthermore, the impact of varying the production mix between suppliers is investigated. The investigation includes assessing how these changes affect lead times, cost efficiency, and safety stock levels in order to mitigate the risk of supply chain disruptions. Each scenario is evaluated based on its ability to maintain service level while optimizing total supply chain costs. This comprehensive scenario analysis is designed to identify robust strategies that can adapt to changing market conditions and customer demands, thereby ensuring that TSI maintains its competitiveness in the market.

(ii) *Develop the Optimal Distribution Strategy*
How can TSI implement strategies to refine inventory locations and levels, thereby guaranteeing the consistent availability of adjustable bases in the face of global supply chain unpredictability? To address this question, we construct a network optimization model that that minimizes costs. We leverage data from TSI's current operations including current distribution flow paths, historical demand and demand forecasts, and supplier sourcing information. Our model provides insights and recommendations for sourcing

decisions, inventory flow paths, and inventory positioning in the network.

The essence of this project is to develop a model to serve as a pivotal reference for TSI, guiding strategic decisions and operational enhancements. The model we develop will help TSI establish a more agile, cost-effective, and robust supply chain, adept at navigating the volatility of global supply chains while maintaining the steady availability of adjustable bases for their customers.

1.3 Project Goals and Expected Outcomes

Project goals. To assist TSI decision-makers in identifying the most effective supply chain network, this project develops an optimization model for adjustable bases. The model defines optimal inventory levels, replenishment strategies, and supplier sourcing decisions to create the optimal supply chain distribution network. The optimal network design is defined as the most cost-effective strategy capable of meeting customer demand and maintaining necessary service level while operating within the operational constraints such as limited facility capacities and meeting minimum supplier capacity requirements.

The model also explores different scenarios by simulating various shipping strategies such as Direct-to-DC only, Hub-and-Spoke shipping within the same region, and Hub-and-Spoke shipping across regions. These scenarios enable TSI to better understand how different routing options impact costs. Additionally, it provides insights into the potential benefits and risks associated with each route configuration. This analysis assists decision-makers at TSI in making informed choices about opening new routes or modifying the existing supply chain network.

Building on the insights from the routing scenarios, another key focus of the model is to evaluate production strategies across different geographies. Producing in locations closer to North American customers has benefits, including lower lead times and a quicker response to changing demand, but it comes with higher costs compared to the current sources of supply from Asia. The model quantifies the cost premium associated with nearshore sourcing to enable TSI to make more informed decisions.

Deliverables. The project deliverables include:

1. *Scenario Simulation Model:* This model optimizes cost across TSI's supply chain network, considering different sourcing strategies and supplier mixes (Asia vs. Nearshore), distribution strategies (Direct-to- DC vs. Hub-and-Spoke), and routing options (variations in available shipping lanes). The model enables TSI to simulate and compare multiple scenarios to identify the most efficient distribution strategies under varying conditions.

2. *Forward-Looking Analytical Model:* This model leverages TSI's weekly forecasts and current operational settings to optimize routing and cost structures across its supply chain network. Designed to serve as a dynamic operational reference, it enables TSI to continuously assess and refine their strategies based on weekly real-time data. This proactive tool helps TSI adapt to market changes and ensures operational agility and cost efficiency.

1.4 Overview of Report

The remainder of the report is structured as follows: Section 2 reviews existing literature on network design and inventory management strategies relevant to our project, including a discussion of location-inventory problem model formulations. Section 3 provides the detailed formulation of our model. Section 4 elaborates on our modeling approach, providing an overview of the data used, additional design considerations, and the approach for conducting scenario modeling. Section 5 presents our results and findings, followed by a discussion on managerial insights and recommendations derived from the results. The report concludes with Section 6, which summarizes the project's key outcomes and identifies potential areas for future research.

2 State of the Practice

Over the past few decades, the landscape of supply chain management and network design has been profoundly influenced by globalization and the fluctuating demands of consumers. Globalization has extended supply chains beyond local and national boundaries, creating complex global networks. This transformation presents both significant challenges and substantial opportunities. Companies now navigate intricate international logistics and diverse regulatory environments as they manage operations across continents. These complexities necessitate advanced network designs that not only efficiently handle international trade but also strategically optimize key cost factors such as ocean freight, inland logistics, and inventory holding costs. The ultimate goal is to minimize these costs while ensuring that inventory levels are optimally balanced to meet dynamic market conditions and consumer needs effectively.

This section examines why U.S. companies began to consider near-shoring or locating production in neighboring countries. It also explores current best practices in network design optimization and concludes with an evaluation of methods for inventory optimization.

2.1 Production Strategies

During the 1960s and 1970s, many U.S. manufacturers relocated production to Asia to capitalize on low-cost labor and a large workforce, adopting offshoring as a competitive strategy. This approach offered significant labor cost savings but also introduced risks related to long lead times, complexities of cross-border shipping, currency fluctuations, political instability, and evolving trade regulations (Schmidt & Wilhelm, 2000).

The trend towards locating manufacturing operations in faraway countries began to change in the 2010s. U.S. companies began to consider near-shoring or locating production in neighboring countries like Mexico for a variety of reasons. Companies begin to see that they could still benefit from low-cost labor while also mitigating some of the risks with Asian production, especially long lead times. Trade between the U.S. and Mexico became less restrictive and more predictable, with agreements like NAFTA and, later, USMCA. Lead times are much shorter from nearshore countries, leading to the ability to respond more quickly to changing consumer demand and a reduction in the requirement for holding as much inventory.

With consumer expectations growing with things like e-commerce, inventory management has become that much more important (Daskin et al., 2002). To achieve both the cost savings of Asian production and responsiveness of near-shored production like Mexico, many organizations have taken a dual-production approach.

2.2 Network Design

Globalization has reshaped corporate strategies, driving companies to seek more efficient and cost-effective ways to enhance shareholder value. A deep understanding of global logistics networks is critical. Schmidt and Wilhelm (2000) provides a clear framework that categorizes multi-national logistics network design into strategic, tactical, and operational levels. The strategic level involves designing the logistics network, including deciding on facility locations and defining facility capacities. The tactical level concerns material flow management, including the flow of materials from suppliers to facilities and from facilities to customers. The operational level focuses on operations that ensure timely delivery to both facility and customers, fulfilling a specific service objective. Our study will focus on the tactical and operational levels to improve decision making processes.

Expanding upon the framework of Schmidt and Wilhelm (2000), we turn to the research conducted byAmiri (2006), which focuses on optimizing the distribution network using a mixed integer programming. The core objective of this model is to minimize network costs while ensuring that the demand of all customers is met without exceeding the capacities of the warehouses and facilities. In order to achieve the objective, Amiri (2006) identifies the trade-offs required to enhance the efficiency and cost-effectiveness of the distribution network.

Additionally, we draw on the work of Hinojosa et al. (2000), who developed a mixed integer programming model to strategically place facilities across various distribution levels. The model aims to minimize costs while ensuring that demand is met in each period, total unit deliveries do not exceed facility capacities, and maintaining certain inventory levels. This research approach provides a critical foundation for our work, particularly in defining the constraints necessary for constructing our network optimization model.

2.3 Inventory Management

In the field of supply chain management, significant attention has been directed towards optimizing two-echelon networks. Comprehensive studies by Melo et al. (2009) and Hinojosa et al. (2008) have advanced our understanding in this area. Melo et al. 2009, in their extensive review, underscore the importance of integrating facility location decisions with other supply chain decisions to enhance the planning of two-echelon networks. Additionally, Ambrosino and Grazia Scutellà (2005) discusses two analytical approaches: optimizing good flows within established networks and network configuration to determine optimal inventory holding and efficient distribution and replenishment of inventory. Together, these studies provide a framework for addressing the challenges in managing two-echelon supply chain networks, critically important given our capstone's questions around multi-echelon optimization.

Building upon the insights of optimizing two-echelon networks, Farahani et al. (2015)

delve into location-inventory problems (LIP), presenting models that minimize total costs, incorporating transportation, product purchasing, ordering, and holding cost. This research highlights the trade-offs between ordering and holding costs, a fundamental aspect of inventory strategy. Furthermore, the work of Daskin et al. (2002) on an integrated inventory-location model introduces an approach that combines facility location decisions with inventory management at distribution centers. The approach is crucial for reducing total logistics costs while maintaining high service levels across the network. Together with Amiri (2006) and Zheng et al. (2019) contribute to this exploration with a model that optimizes ordering patterns, such as the frequency and quantity of orders, emphasizing the importance of coordinated inventory management across the supply chain.

Our literature review provides a comprehensive understanding of how globalization and shifting production strategies shape supply chain management. Companies are adapting by balancing cost efficiency with market responsiveness through nearshore supplier and dual-supplier approaches. Consequently, network optimization and inventory management emerge as key focus areas. Efficient material flows are critical for minimizing costs while meeting customer demands. Overall, our research emphasizes the importance of an integrated approach that balances strategic network design decisions with tactical and operational inventory management strategies.

3 Methodology

In this section, we present our methodology. We begin with a brief overview of the literature that motivated the formulation followed by a review of the mathematical formulation of the model.

3.1 Motivation

Our model formulation, particularly the objective function, is motivated by the basic LIP proposed by Farahani et al. (2015). We optimize for the total costs of the distribution network, including the costs associated with product purchasing, inbound transportation from suppliers, internal transportation of inventory between echelons, facility inventory handling, and inventory holding. Following Amiri (2006), our model decides the optimal flow of units between nodes in the network given capacity-constrained supply and intermediary nodes.

Our model differs from the previously mentioned formulations in that we do not make facility location and capacity decisions; we assume both are given a priori. We focus on inventory flows and sourcing decisions rather than facility location or customer demand allocation decisions.

Moreover, our model extends these previous formulations by allowing a demand node to be serviced by multiple supply nodes, as opposed to using a binary variable to associate a single supply node with a demand node in the basic LIP. Additionally, we consider demand across multiple time periods. We allow for ordering from suppliers and holding inventory across the same time horizon.

3.2 Mathematical Formulation

Notation. We begin with a review of the notation for all sets, parameters, and variables used in our model. Table 1 summarizes the sets considered in our model, Table 2 summarizes the parameters, and Table 3 summarizes the variables.

Table 1
Model Sets

Symbol	Description
P	Set of product SKUs, indexed by p
S	Set of suppliers, indexed by s
H	Set of hubs, indexed by h
W	Set of distribution centers (DCs), indexed by w
F	Set of all TSI facilities in network, determined by the union of hubs h and distribution centers w, indexed by f
A	Set of arcs, indexed by a

Table 2
Model Parameters

Symbol	Description	Units
Cost		
κ_{ps}^{Prod}	product cost of $p \in P$ produced by supplier $s \in S$.	[$/unit]
κ_{a}^{Trans}	transportation cost per load on arc $a \in A$.	[$/load]
κ_{pf}^{Hand}	handling cost of each unit $p \in P$ received at facility $f \in F$.	[$/unit]
κ_{pft}^{Inv}	holding cost of each unit of inventory $p \in P$ at facility $f \in F$ at time period $t \in T$.	[$/unit/period]
υ_{pw}	penalty cost per unit of demand of product $p \in P$ not fulfilled at DC $w \in W$.	[$/unit]
Demand		
δ_{pwt}	demand for product $p \in P$ at DC $w \in W$ at time $t \in T$.	[units]
σ_{pw}^{SLev}	minimum service level of demand that must be filled of product $p \in P$ at DC $w \in W$.	[%]
Operational		
θ_{pt}^{SS}	total safety stock of product $p \in P$ required to be held in the network at time $t \in T$.	[units]
ι_{ht}^{SS}	the minimum proportion of total safety stock required to be held at hub $h \in H$ at time $t \in T$.	[%]
ψ_{pwt}^{SS}	safety stock of product $p \in P$ required to be held at DC $w \in W$ at time $t \in T$.	[units]
τ_{ps}^{TCap}	portion (space) that one unit of product $p \in P$ consumes on an inbound transportation load from supplier $s \in S$.	
τ_{ph}^{TCap}	portion (space) that one unit of product $p \in P$ consumes on an internal transportation load from hub $h \in H$.	
γ_{s}^{TCap}	total capacity of an inbound transportation load from supplier $s \in S$.	
λ_{a}	lead time on arc $a \in A$.	[weeks]
ϵ_{f}^{SCap}	total storage capacity, across all products, at facility $f \in F$.	[units]
μ_{st}^{Prod}	maximum production capacity of supplier $s \in S$ at time $t \in T$.	[units]
ρ_{st}^{Prod}	minimum production requirement of supplier $s \in S$ at time $t \in T$.	[units]
α_{pf}^{Inv}	initial inventory of product $p \in P$ held at facility $f \in F$ in time period 0.	[units]

Table 3
Model Decision Variables

Symbol	Description
o_{psft}	continuous variable representing the number of units of product $p \in P$ ordered from supplier $s \in S$ for destination $f \in F$ at time $t \in T$.
e_{pft}	continuous variable representing the number of units of product $p \in P$ held at facility $f \in F$ at time $t \in T$.
m_{phwt}	continuous variable representing the number of units of product $p \in P$ internally transferred from hub $h \in H$ to DC $w \in W$ at time $t \in T$.
d_{pwt}	continuous variable representing the number of units of product $p \in P$ consumed by demand at DC $w \in W$ at time $t \in T$.
r_{psft}	continuous variable representing the number of units of product $p \in P$ received at facility $f \in F$ from supplier $s \in S$ at time $t \in T$.
r_{phwt}	continuous variable representing the number of units of product $p \in P$ received at DC $w \in W$ from hub $h \in H$ at time $t \in T$.
l_{sft}	integer variable representing the number of loads shipped from supplier $s \in S$ to facility $f \in F$ at time $t \in T$.

Formulation. Given this notation, we formulate the cost minimization objective and constraints of our problem as:

$$\text{Minimize} \quad B_1 + B_2 + B_3 + B_4 + B_5 + B_6 + B_7, \tag{1}$$

where

$$B_1 = \sum_{p \in P} \sum_{\substack{(s,f) \in A \\ s \in S, f \in F}} \sum_{t \in T} \kappa_{ps}^{Prod} \cdot o_{p(s,f)t}, \tag{2}$$

$$B_2 = \sum_{\substack{(s,f) \in A \\ s \in S, f \in F}} \sum_{t \in T} \kappa_{(s,f)}^{Trans} \cdot l_{sft}, \tag{3}$$

$$B_3 = \sum_{p \in P} \sum_{\substack{(h,w) \in A \\ h \in H, w \in W}} \sum_{t \in T} \kappa_{(h,w)}^{Trans} \cdot (m_{phwt} / \tau_{ph}^{TCap}), \tag{4}$$

$$B_4 = \sum_{p \in P} \sum_{f \in F} \sum_{t \in T} \kappa_p^{Inv} \cdot e_{pft} \tag{5}$$

$$B_5 = \sum_{p \in P} \sum_{s \in S} \sum_{f \in F} \sum_{t \in T} \kappa_f^{Hand} \cdot r_{psft}, \tag{6}$$

$$B_6 = \sum_{p \in P} \sum_{h \in H} \sum_{w \in W} \sum_{t \in T} \kappa_f^{Hand} \cdot r_{phwt}, \tag{7}$$

$$B_7 = \sum_{p \in P} \sum_{w \in W} \sum_{t \in t} \upsilon_{pw} \cdot (\delta_{pwt} - d_{pwt}), \tag{8}$$

subject to

$$\sum_{p \in P} e_{pft} \leq \epsilon_f^{SCap} \qquad f \in F, t \in T, \tag{9}$$

$$\rho_{st}^{Prod} \leq \sum_{p \in P} \sum_{f \in F} o_{psft} \leq \mu_{st}^{Prod} \qquad s \in S, t \in T, \tag{10}$$

$$r_{psft} = o_{psf(t-\lambda^{(s,f)})} \qquad p \in P, s \in S, f \in F, t \in T, \tag{11}$$

$$r_{phwt} = m_{phw(t-\lambda^{(h,w)})} \qquad p \in P, h \in H, w \in W, t \in T, \tag{12}$$

$$e_{pf(t=0-max(\lambda))} = \alpha_{pf}^{Inv} \qquad p \in P, f \in F, \tag{13}$$

$$e_{pht} = \sum_{s \in S} r_{psht} + e_{ph(t-1)} - \sum_{w \in W} m_{phwt} \qquad p \in P, h \in H, t \in T, \tag{14}$$

$$e_{pwt} = \sum_{s \in S} r_{pswt} + \sum_{h \in H} r_{phwt} + e_{pw(t-1)} - d_{pwt} \qquad p \in P, w \in W, t \in T, \tag{15}$$

$$e_{pwt} \geq d_{pwt} \qquad p \in P, w \in W, t \in T, \tag{16}$$

$$e_{pht} \geq \sum_{w \in W} m_{phwt} \qquad p \in P, h \in H, t \in T, \tag{17}$$

$$(\delta_{pwt} \cdot \sigma_{pw}^{SLev}) \leq d_{pwt} \leq \delta_{pwt} \qquad p \in P, w \in W, t \in T, \tag{18}$$

$$\sum_{p \in P} (o_{psft} \cdot \tau_{ps}^{TCap}) \leq (l_{sft} \cdot \gamma_s^{TCap}) \qquad s \in S, f \in F, t \in T, \tag{19}$$

$$\sum_{h \in H} e_{pht} \geq \theta_{pt}^{SS} \qquad p \in P, t \in T, \tag{20}$$

$$e_{pht} \geq (\iota_{ht}^{SS} \cdot \theta_{pt}^{SS}) \qquad p \in P, h \in H, t \in T, \tag{21}$$

$$e_{pwt} \geq \psi_{pwt}^{SS} \qquad p \in P, t \in T, \tag{22}$$

$$l_{sft} = \in \{0, 1, ...n\} \qquad s \in S, f \in F, t \in T, \tag{23}$$

$$o_{psft} \geq 0 \qquad p \in P, s \in S, f \in F, t \in T, \tag{24}$$

$$m_{phwt} \geq 0 \qquad p \in P, h \in H, w \in W, t \in T, \tag{25}$$

$$d_{pwt} \geq 0 \qquad p \in P, w \in W, t \in T, \tag{26}$$

$$e_{pft} \geq 0 \qquad p \in P, f \in F, t \in T, \tag{27}$$

$$l_{sft} \geq 0 \qquad s \in S, f \in F, t \in T, \tag{28}$$

$$r_{psft} \geq 0 \qquad p \in P, s \in S, f \in F, t \in T, \tag{29}$$

$$r_{phwt} \geq 0 \qquad p \in P, h \in H, w \in W, t \in T. \tag{30}$$

The objective function (1) seeks to minimize the total cost of managing inventory, from purchasing from the supplier to delivering to the customer. The minimization function includes seven cost terms. The first term (2) defines the purchasing costs for all units ordered from suppliers. The second term (3) defines the inbound transportation cost from the supplier to TSI facility. The third term (4) defines the internal transfer transportation cost for moving product between TSI hub and DC facilities. The fourth term (5) defines the cost of holding inventory each time period. The fifth (6) and sixth term (7) define the cost of handling the inventory in and out of the hub and DCs, respectively. The seventh term (8) applies a penalty for any demand unmet.

Constraint (9) ensures that the total inventory held each period does not exceed the storage capacity of the facility. Constraint (10) requires the total units purchased to meet the minimum production requirement from each supplier while not exceeding the maximum production capacity. Constraint (11) ensures the amount of inventory received in the current time period at each facility is equal to the amount of inventory ordered from the supplier in time period t minus the arc's lead time. Constraint (12) ensures the amount of inventory received in the current time period at each DC is equal to the amount of inventory shipped from the hub in time period t minus the arc's lead time. Constraint (13) initializes the amount of inventory held at each facility at time 0. Constraints (14) and (15) are flow constraints to ensure the amount of inventory on hand each time period is equal to what was received in the current period and held last period minus what was shipped in the current period. Constraints (16) and (17) ensure that the units held are greater than or equal to the number of units shipped out or units of demand fulfilled. Constraint (18) ensures the demand fulfilled meets the minimum service level while not exceeding total demand. Constraint (19) ensures that the capacity for the number of loads shipped is greater than the number of units shipped. Constraint (20) ensures that the summation of inventory on hand across all hubs at each time period is greater than the unit safety stock requirement for the network. Constraint (21) ensures that each hub holds a minimum percentage of the network-level safety stock requirement at each time period. Constraint (22) ensures that the inventory on hand at each DCs is greater than the safety stock requirement specific to the DC. Constraint (23) ensures the number of inbound loads from a supplier is an integer. Constraints (24) through (30) ensure non-negativity for the decision variables.

4 Analysis Approach

This section builds on the formulation presented in Section 3 by providing further details on our modeling approach. We begin with an overview of our data. Then, we discuss additional modeling considerations, including how time periods and safety stock levels are defined. We conclude the section with a review of our approach for conducting scenario analysis.

4.1 Data

Table 4 provides an overview of the data used in our model. The subsections discuss each data element in further detail.

Table 4
Data Overview

Category	**Data Element**	Num. of Data Points	Units
Demand			
	Product SKUs	24	[skus]
	Historical Sales	9,360	[units/week/sku/dc]
	Sales Forecast	21,216	[units/week/sku/dc]
	Minimum Service Level	1	[%]
Facilities			
	Type	3	
	Locations	16	[nodes]
	Storage Capacity	14	[units]
	Handling Cost	14	[$/unit]
	Holding Costs	24	[$/unit/time period]
Inventory			
	Current Inventory on Hand	14	[units]
	Days of Supply Targets	336	[days]
Supplier			
	Product Cost	48	[$/unit]
	Minimum Production Requirement	2	[units/week]
	Maximum Production Capacity	2	[units/week]
Transportation Arcs			
	Rates	61	[$/load]
	Available Lanes	61	[lanes]
	Load Capacity	72	[units/load/origin/product]
	Lead Time	61	[weeks]

4.1.1 Demand

Our project focuses on TSI's adjustable base category, which consists of 24 SKUs across four product families. We use blinded product names to protect sensitive TSI information; product families are referred to as A, B, C, and D, with the subsequent number denoting the specific product SKU. For example, SKU three in product family B is labeled as B3.

TSI fulfills demand for their adjustable bases through various retail channels. Demand from the retail channels are fulfilled through the DCs. For the scope of our project, demand is aggregated to the DC level rather than individual stores or end customers. We consider DCs as our demand nodes. Weekly historical sales were provided at the product SKU/DC level for a 10-month period from January to October 2023.

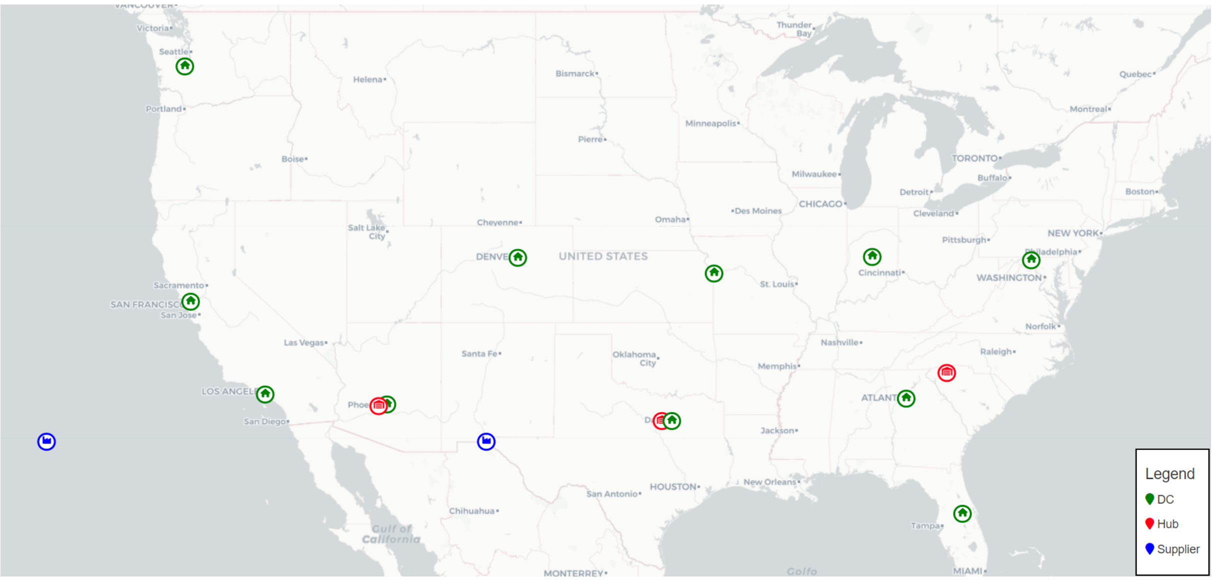
TSI also provided a weekly data file with the demand forecast for the next year at the product, DC, and week level. This forecast was used in our forward-looking model discussed in Section 4.3

TSI provided a minimum service level to be adhered to. The minimum service level is defined as the minimum percentage of demand that must be fulfilled each time period.

4.1.2 Facilities

Figure 2 provides a map of TSI's distribution facilities. The color of the nodes represents the type of facility. The 11 green icons represent DCs. DCs can receive inventory from suppliers and hubs, hold inventory, and fulfill demand. The three red icons represent hubs. The hubs can receive inventory from suppliers, hold inventory, and ship inventory to the DCs. The two blue icons represent the supplier locations. For visualization purposes, the Asian supplier is shown closer to the United States while the nearshore supplier is shown at the U.S. border. Suppliers can produce products and ship to hubs and DCs.

Figure 2
TSI Distribution Facilities



Each DC has a maximum storage capacity defined as the number of total units, regardless of product, that can be held at the facility. In our model, hubs are unconstrained; they do not have a defined storage capacity.

Each facility, inclusive of hubs and DCs, has a unique cost associated with handling a unit of inventory. Based on a recent study conducted by TSI, cost per unit-in and cost per unit-out for each facility was provided. The unit-in and unit-out costs were added to get a per-unit handling cost. Our model assumes each unit that is received at a facility is eventually shipped out. Thus, each unit incurs the total per-unit handling cost on receipt at the facility.

Holding costs are incurred on a per-unit basis during each time period the unit is held at a facility. Holding costs are incurred at both hubs and DCs and are a fixed annual percentage of the product cost. Given different product costs between suppliers, we use the average product cost when determining the per-unit holding cost. The average product cost is multiplied by the annual percentage holding costs and divided by 52 weeks in a year to get a per-unit, per-time period holding cost specific to each product SKU. The holding cost for product SKU does not vary across facilities.

4.1.3 Inventory

To initialize our model, we provide the model with an initial inventory on hand value at time period 0. An inventory-on-hand report was generated to determine the current inventory level of each product at each facility. Our model considers initial inventory to be the actual inventory on hand as of March 2024.

TSI currently manages its inventory levels based on days of supply target for each product/facility combination. To determine TSI's current target unit inventory levels used for planning, we multiply the average daily demand and days of supply target. This provides a target inventory level, in units, at the product/facility level. The definition of target inventory levels is discussed further in Section 4.2.

4.1.4 Supply

Product costs vary among suppliers. For each of the 24 product SKUs, a per-unit purchasing cost for each supplier was provided. In current operations, the nearshore supplier can produce only the seven product SKUs in product family A. For our project, should-costs for the other 17 product SKUs were provided.

As referenced earlier, TSI has historically sourced most of its adjustable base product from Asia but has begun to develop a capability for supplier production nearshore. Given TSI's effort to build out the nearshore supplier's capability and the desire to maintain balanced supplier ordering across time periods, minimum production quantities are defined. The minimum production requirement is defined as the number of units, regardless of product, that must be ordered from each supplier every time period. For our model, we divide the monthly production requirement by four, considering an average of four weeks per month, to get a weekly minimum production requirement.

Similarly, each supplier has a maximum production capacity, which is defined as the maximum number of units that can be ordered from the supplier during a given time period. The maximum production capacity is divided by four the get the weekly maximum production capacity.

4.1.5 Transportation Cost

Transportation rates were collected for all arcs (lanes) within the network. In total, 61 lanes are defined, consisting of 28 lanes from supplier to TSI facilities and 33 lanes between hubs and DCs within TSI's domestic network. The rates include ocean rates from Asia to all facilities, truckload rates from the nearshore supplier to all facilities, and truckload rates for product moved within the domestic network between hubs and DCs. All rates in our model are flat, door-to-door rates. For ocean lanes, a blended contracted/spot rate was defined for the lane costs. For truckload lanes, contracted rates were used where available. Where contracted rates were unavailable, spot rates were provided by TSI's 3PL partner.

Lead times were provided for all suppliers to TSI facility lanes. Lead time is defined as the number of time periods between order placement with the supplier and receipt of the inventory at the destination facility. Values range from 9 to 13 weeks for the Asian supplier and are set at 4 weeks for the nearshore supplier. For loads transferred between hubs and DCs, a 1-week lead time is used to account for order processing, handling, and shipping. This means that if an internal transfer is shipped in the current time period, the inventory will be available at the destination facility in the next time period.

While rates were collected for all potential lanes within the network, TSI does not regularly ship on all lanes. To model current shipping patterns, we develop our model with the capability to make lanes available or unavailable. When lanes are unavailable, no units can be shipped on the lane. The availability of lanes is applicable for lanes between supplier and TSI facility and for lanes between hubs and DCs.

TSI's product SKUs vary in dimensions. Additionally, the types of transportation modes used in the network have varying capacities. Rather than defining transportation modes explicitly, we associate the origin facility with a mode. The Asian supplier ships ocean containers while all other nodes in the network ship truckloads.

These factors make it necessary to define the number of units, by product and origin, that fit on a transportation move. The number of units that fit on a container/trailer was provided by product/origin location. For example, for product C1, 250 units can fit on an ocean container and 350 units fit on a truck.

This data is used in our model to determine the number of loads required for shipping a given number of units ordered or shipped internally in the network.

4.2 Additional Considerations

This subsection discusses considerations that do not impact our formulation but are important in the design of our model, namely how time periods and safety stock requirements are defined.

Time. Our model aims to simulate the impact of design changes to existing supply chain operations, without starting up or winding down the distribution network. Therefore, while the model considers 52 time periods (weeks) of demand, we allow inventory to be already in transit before the demand period starts. To accommodate this, ordering is permitted prior to the first demand period. Without this provision, there's a risk that inventory would not be available as demand begins. To account for the maximum supplier lead time of 13 weeks across all suppliers and products, we start our model at time period -13.

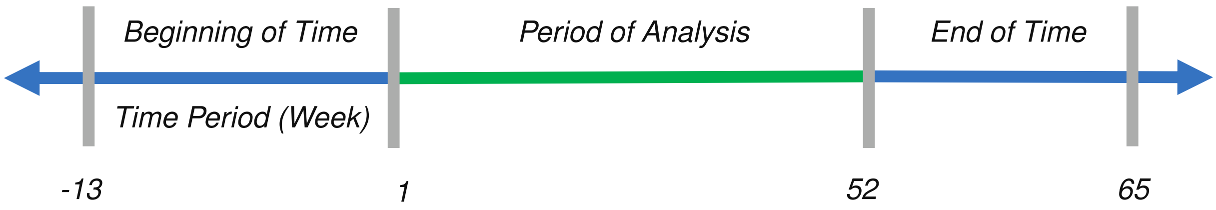
Similarly, we add 13 time periods of demand to the end of our model. Thus, the last time period is 65. Defining the end of time periods ensures that ordering for the supplier does not stop prior to time period 52.

The results and analysis presented throughout this report represent the 52 time periods of operations. The results analysis does not consider the beginning of time and end of time periods. Figure 3 illustrates the time periods in our model.

Safety Stock. Given that we consider DCs as demand consumption points, we require the hubs, rather than the DCs, to hold safety stock unless otherwise noted in the scenario.

To determine the safety stock requirement, we aggregate product level demand across all DCs in the network. We determine the weekly mean and standard deviation by product

Figure 3
Illustration of Time Periods Considered



across the network. Using the minimum service level as a confidence level and a lognormal demand distribution (discussed in detail in Section 4.3.1), we calculate a minimum safety stock level per product at the network level. The summation of inventory at all hubs must be greater than the minimum safety stock requirement for all time periods.

We introduce a lead time variability factor into the total safety stock requirement. For each supplier, we determine the lead time standard deviation in number of weeks. Using a normal distribution and confidence interval parameter, we determine a factor for the number of weeks above the mean that should be held in safety stock given the variability in lead time. The Asian supplier has a larger standard deviation in lead times, thus the factor representing the variability in Asian shipments is greater than the nearshore suppliers. We add the safety stock factor for each supplier and multiply this factor by the unit safety stock requirement to derive a safety stock requirement considering lead time variability. Considering lead time variability between suppliers allows for improved quantification of the trade-off between near and offshore suppliers as lead time variability directly affects how much safety stock must be held in the network.

To ensure that one hub does not hold all safety stock, we set a minimum allocation percentage for each hub. The minimum allocation percentage is multiplied by the network-level safety stock requirement to derive a hub-level safety stock requirement. The model decides where to hold the remaining safety stock after the minimum allocation at each hub is met.

We also calculate safety stock requirements based on TSI's current day of supply targets. Each product and DC combination has a day of supply target. We multiply the average daily demand by the day of supply target to derive the unit safety stock requirement.

4.3 Scenario Analysis

We utilize our model for two purposes. First, we conduct a strategic network design analysis to quantify the impacts of supply and network configuration changes. We use a Monte Carlo simulation to run each scenario across many potential demand realizations. Second, we leverage the model to optimize forward-looking planning decisions. In the forward-looking model, we use TSI's current operational constraints, current inventory on hand, and the demand forecast for the next year to optimize the ordering and internal transfer decisions on a weekly basis. This approach allows TSI to analyze long-term design decisions while also gaining value in the short-term from optimized replenishment planning.

Scenarios were identified based on 'what-if' questions proposed during the initial stages of our project. The questions were classified into two scenario categories: supply impacts and TSI network configurations. Supply impacts refer to changes to supplier production capabilities, for example, what product SKUs the supplier can produce and production requirements, such as minimum and maximum production volumes. Network configurations refer to changes in available shipping lanes and availability of facilities.

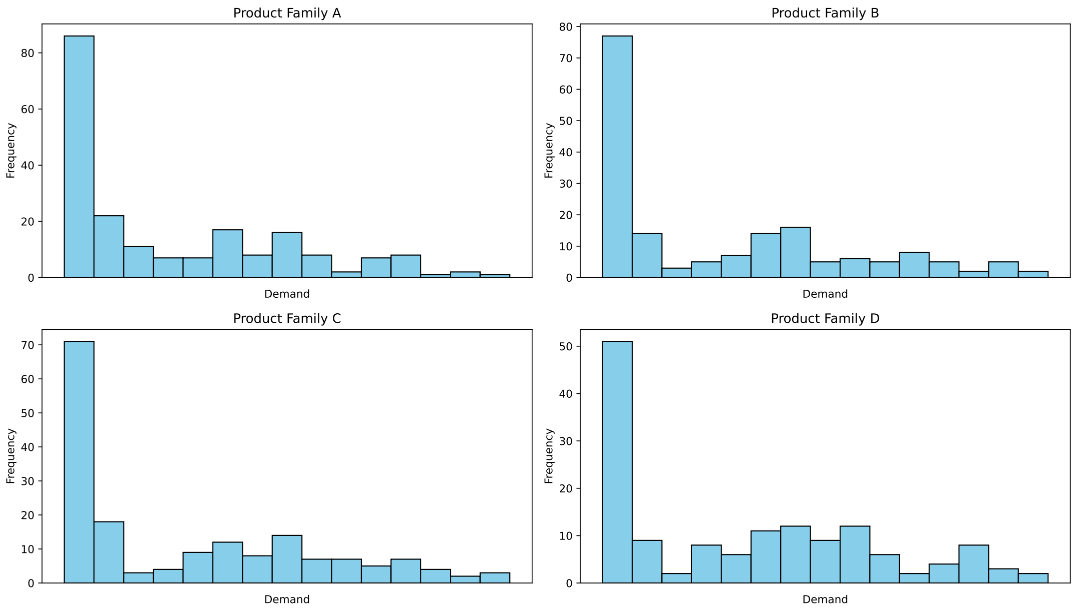
Based on the questions proposed, we develop ten scenarios for analysis to provide a quantitative method to understand the impact of various supply and network configuration decisions. A summary of the scenarios is shown in Table 5.

4.3.1 Monte Carlo Simulation

We test each scenario across a set of demand instances using a Monte Carlo simulation. A demand instance refers to a random generation of one year's worth of data across all products and DCs. While our model is deterministic, by running each scenario across many demand instances, we capture fluctuations in demand to ensure a robust solution.

Demand Generation. To develop the set of random demand instances, we fit various statistical distributions to TSI's historical demand data for each product/DC combination. Figure 4 shows the distribution of historical demand occurrences aggregated to the product family. We see a high frequency of demand occurrences at low volumes with a significant right tail of less frequent but high-volume demand occurrences.

Figure 4
Distribution of Historical Demand by Product Family

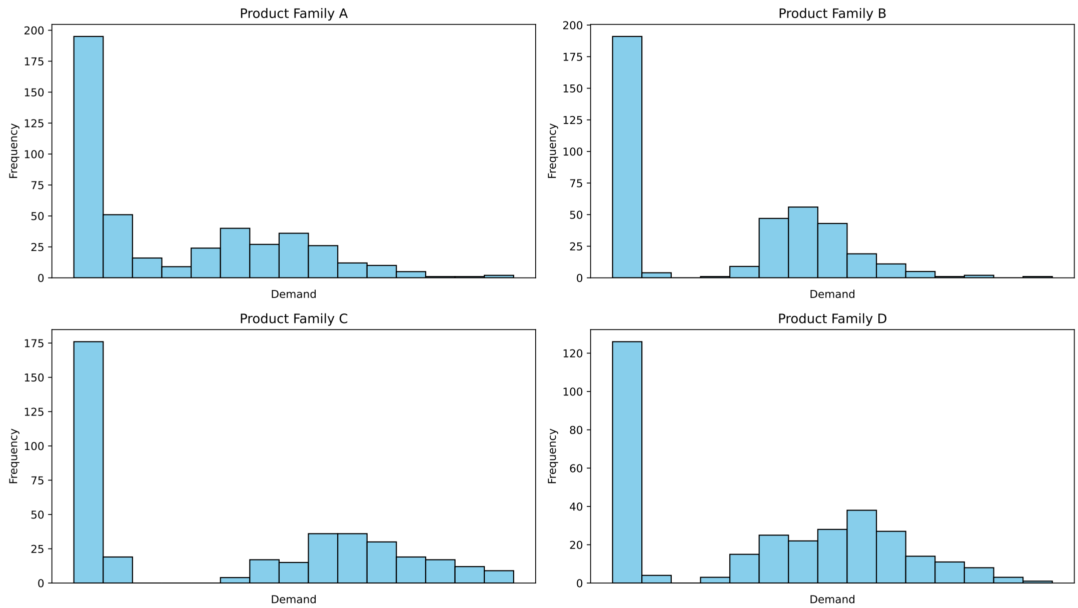


We find a lognormal distribution best fits TSI's historical demand. The lognormal is the ideal distribution for our data given its inherent characteristic of a natural right-skew. Based on the characteristics of the lognormal distribution, when a logarithm function is applied to our demand data, we find a normal distribution. The density function for the lognormal distribution is shown in equation (31).

$$f_X(x) = \frac{1}{x\sigma\sqrt{2\pi}} \exp\left[-\frac{(\ln x - \mu)^2}{2\sigma^2}\right] \tag{31}$$

After fitting the lognormal distribution with each product/DC's mean and standard deviation, we randomly select a demand value from the distribution for each of the 52 time periods. Using the random selection of demand values for each time period, we create a demand instance for one year's worth of demand for all product/DC combinations. We repeat this process to create a set of 25 demand instances. Figure 5 shows the distribution of one demand instance randomly generated.

Figure 5
Distribution of Randomly Generated Demand by Product Family



Scenarios. We provide a detailed review of the scenarios considered in our Monte Carlo simulation. We first review the design of the current state model (1_CurState). A list of relevant assumptions for all other scenario models is then provided. Finally, we review the deviations from the current state scenario in each of the other scenarios modeled, shown in Table 5.

Our current state model (1_CurState) ships from the Asian and nearshore suppliers with minimum and maximum production constraints. The nearshore supplier can only produce product family A. Shipping is only available on lanes currently used in normal operations. This includes the nearshore supplier only shipping to one hub with the Asian supplier shipping to all three hubs and two identified DC facilities. Internal order transfer (IoT)s, shipments between hub and DC facilities, are only allowed on hub to DC lanes within the same region.

We now discuss the deviations in each scenario from the current state model. Where no specific supply impact or network configuration decisions are defined for the scenario, the following assumptions are considered:

- Nearshore supplier has the ability to produce and ship all 24 product SKUs.
- Each supplier has a fixed monthly minimum production requirement and maximum production constraint. The values are defined and constant across time periods.
- The safety stock requirement for each product is determined at the network level based on a 98 percent service level (Section 4.2). As DCs are demand consumption points, the safety stock is held at hub facilities. There is no explicit requirement for safety stock at DC
- The three hubs are available for receiving products from suppliers and shipping products to DCs.
- All lanes within the domestic TSI network are available for shipping product between hubs and DCs.
- All lanes between each supplier and TSI facilities are available. This includes both hubs and DCs.

In the scenario table (Table 5), we refer to these assumptions as “Base design”.

Table 5
Overview of Scenario Designs

Scenario ID	Supply Impact	Network Configuration
1_CurState	Nearshore supplier can only produce product A	IoTs are only allowed between hub and DCs in the same region. Nearshore supplier only ships to one hub; Asian supplier ships to all hubs and two identified DC facilities
2_BaseOpt	Base design	Base design
3_OnlyAsian	Nearshore supplier produces no product, all product is sourced from Asia	Base design
4_OnlyNear	Asian supplier produces no product, all product is sourced from nearshore	Base design
5_NearProdA	Nearshore supplier can only produce product A	Base design
6_NoSupMin	Suppliers do not minimum product constraints each time period	Base design
7_IoTinReg	Base design	IoTs are only allowed between hub and DCs in the same region
8_AllDir	Base design	Suppliers only ship directly to DCs; no hubs and IoTs exist in the model. DCs are required to hold safety stock based on TSIs existing safety stock targets.
9_AllHub	Base design	Suppliers only ship to hubs; DCs are only replenished through IoTs from hubs.
10_DCSafety	Base design	DCs and hubs are required to hold safety stock based on TSIs existing safety stock targets

4.4 Forward Looking Model

Currently, TSI's supply planners execute weekly planning, taking a 52-week demand forecasts, existing inventory levels, and days of supply inventory targets to determine the purchasing required. We enhance this approach by leveraging our model to optimize replenishment planning using demand forecast and current inventory level. It employs advanced analytics to identify opportunities for cost savings in purchasing, handling, holding, and transportation costs, thereby improving efficiency in purchase order planning and the management of internal shipment transfers. The Forward Looking Model enhances TSI's ability to meet customer demand effectively without incurring unnecessary costs.

Moreover, our model incorporates data analytics on a weekly basis to enhance adaptability, allowing the supply chain to maintain resilience under variable conditions. It effectively determines optimal inventory levels and safety stock within the network across different time periods, significantly reducing the risks associated with excess stock and stock-outs.

The Forward Looking Model will serve as a comprehensive tool for TSI to review and refine operational processes, providing actionable insights for adapting to changes in lead times, supplier capacities, transportation rate, and shipping routes. The capability to adjust parameters will enable TSI to navigate supply chain complexities with increased agility and precision.

The detailed analysis presented in the next section substantiates the effectiveness of our model and its impact on operational efficiency. We provide quantitative results and data-driven evidence supporting the benefits and advantages of this advanced planning model.

5 Results

In this section, we review the results of our scenario modeling. We begin with a quantitative review of the findings. For the Monte Carlo simulation, we review the current state model before an overview of the results from each scenario. We then discuss how the current state model compares to the model we use as our baseline model, which we use for comparison against all other scenarios. Specific scenarios and their comparison to the baseline are reviewed. The forward-looking model results are then discussed. We conclude this section with managerial insights and recommendations.

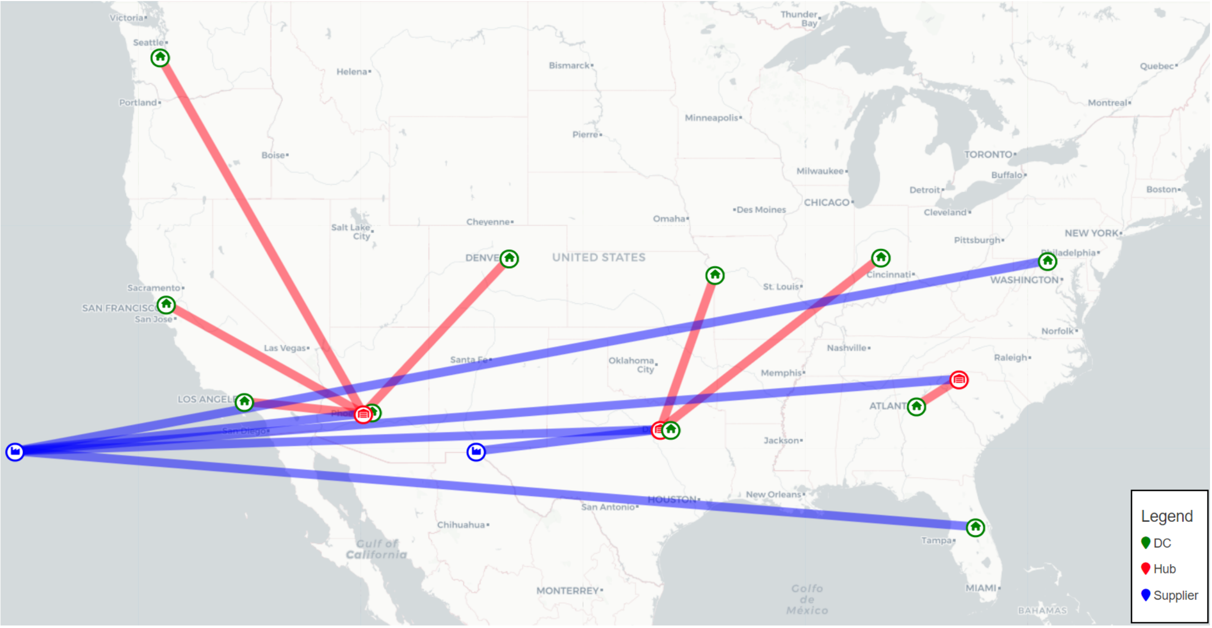
5.1 Scenario Results

5.1.1 Baseline of Current Operations

We first model TSI's network considering their current operational constraints in the 1_CurState model. The operational constraints include making available only the arcs that are used in current operations and constraining the supplier production such that the nearshore supplier can only produce product A.

Figure 6 illustrates the arcs made available in the 1_CurState model. Blue arcs represent moves from the supplier to TSI facilities. Red arcs represent moves from TSI hubs to DCs.

Figure 6
Available Lanes in Current Operations



We present cost and volume details throughout the Results section. To protect TSI, we normalize all results by setting the 1_CurState model to 100 and adjusting all scenarios accordingly. We do this for all costs and volumes (units ordered and inventory held).

5.1.2 Scenario Cost Summary

Figure 7 provides an overview of the average total annual cost for each scenario across the 25 demand instances. The total annual costs are inclusive of product purchase costs, inbound transportation costs, internal transportation transfer costs, inventory handling costs, and inventory holding costs. We find total costs range from \$97.99 to \$101.34.

The distribution of results across demand instances is shown in Figure 8. Across demand instances, we find that the optimal solution based per unit costs, defined as total solution costs divided by demand fulfilled, for each scenario falls within a range of 2 to 4% between the best and worst solution. By running each scenario across many demand instances, we have confidence that our model is robust and provides consistent results for different demand realizations.

Figure 7

Average Total Annual Cost Across Demand Instances

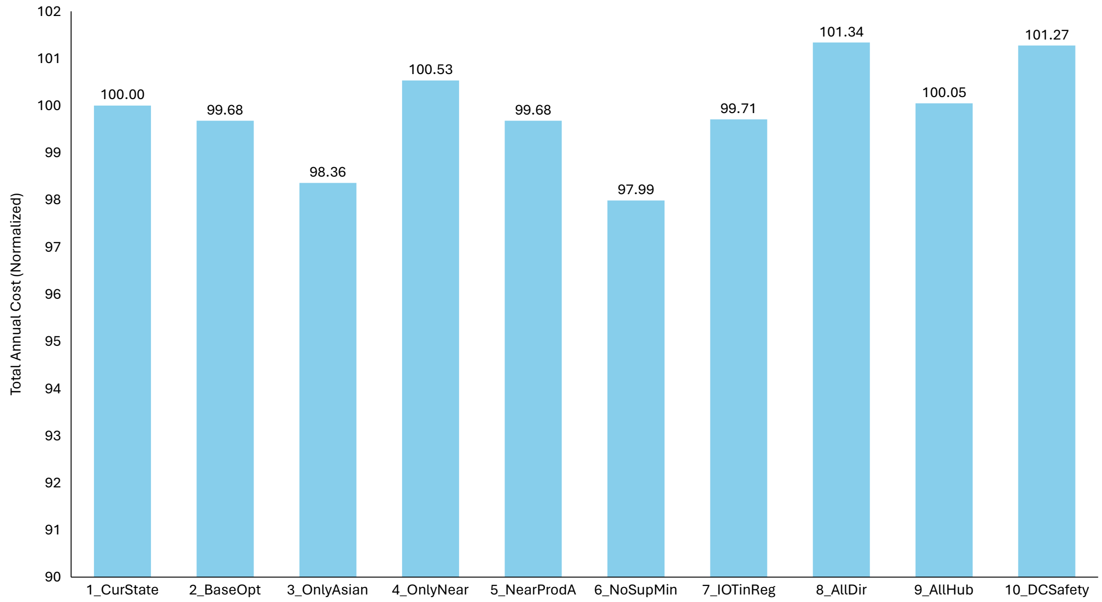
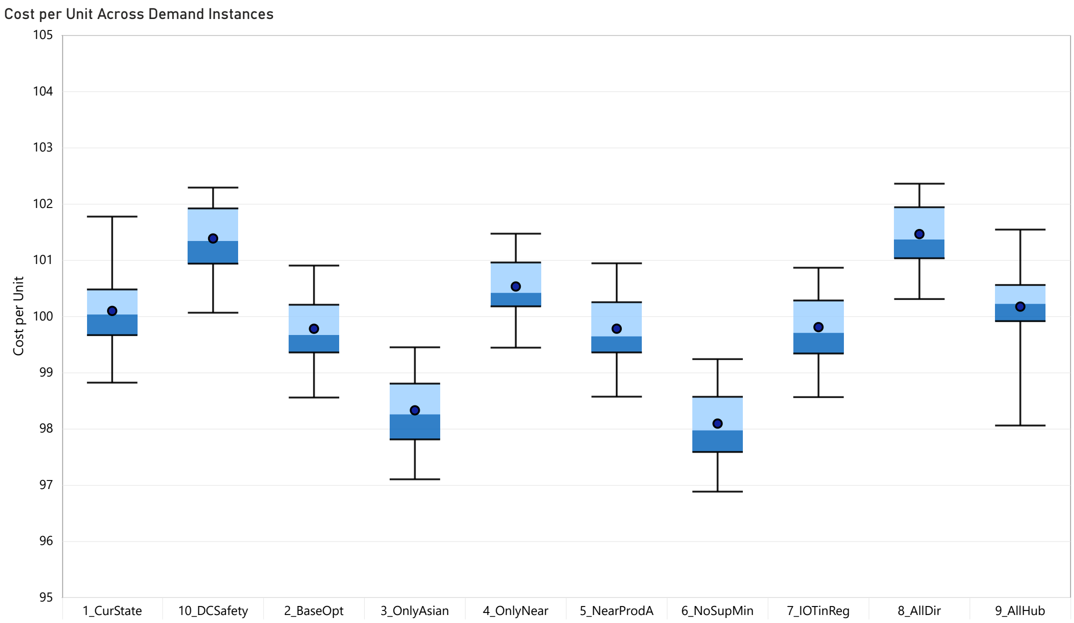


Figure 8

Distribution of Costs per Unit Across All Demand Instances

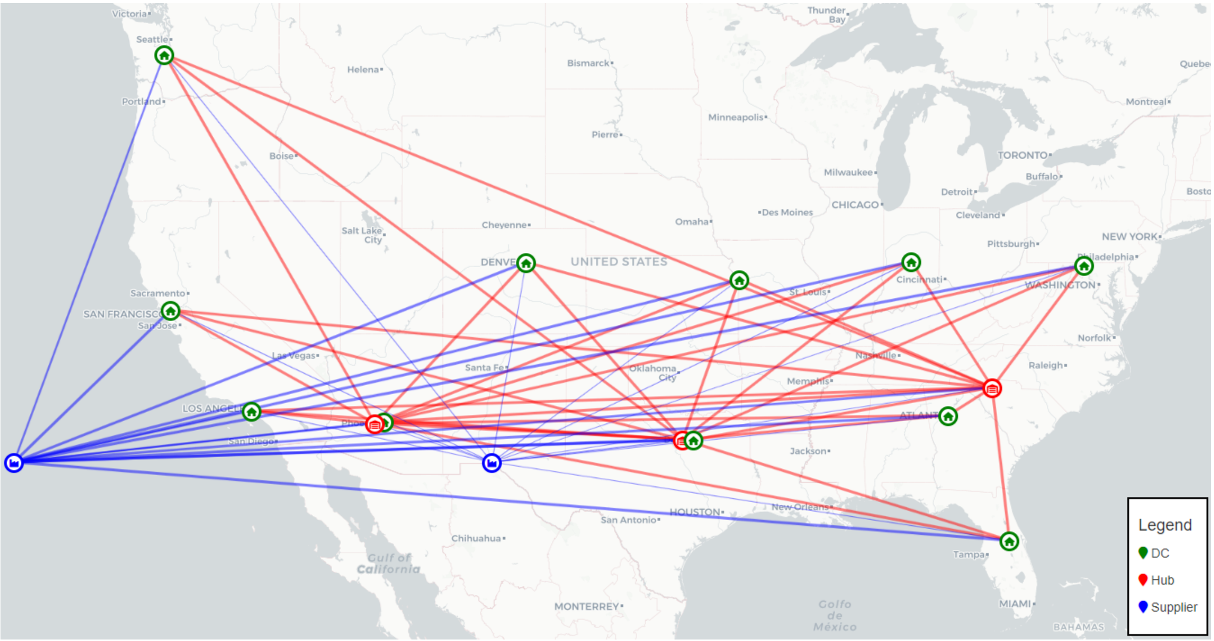


5.1.3 Model-Based Scenario Analysis

We now discuss key results specific to scenarios defined. We first compare the current state model to an optimized baseline model, which we use for all other scenario comparisons. We then compare results for various scenarios including changes in sourcing strategy between the Asian and nearshore suppliers, changes to available shipping lanes, a pure Hub-and-Spoke versus a pure Direct-to-DC model, and shifts in how inventory, specifically safety stock, is allocated throughout the network.

Optimized Baseline. The baseline optimized model, 2_BaseOpt, makes available all lanes within the network, including direct shipping to all DCs, and connects each hub to all DCs. Figure 9 illustrates the arcs available in the 2_BaseOpt model.

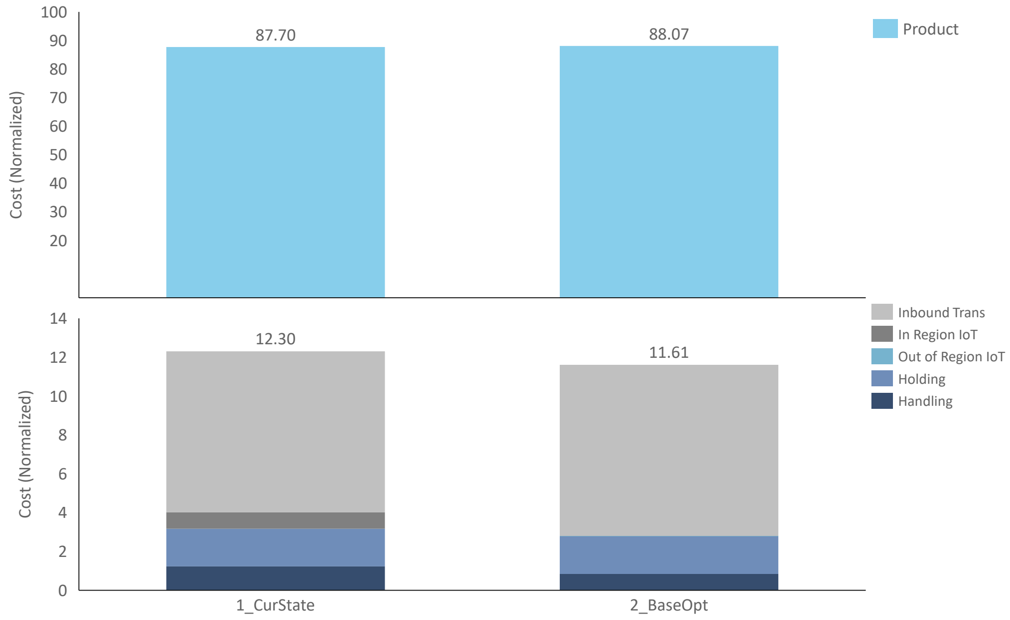
Figure 9
All Available Lanes in Fully Connected Network



Comparing the current state model to the baseline optimized model, we find that allowing direct shipping and connections between all hubs and DCs generates a savings of 0.3%. Figure 10 shows the cost category differences between the two models. The baseline optimized model predominately ships all products from the supplier directly to DCs. Savings are realized from reduced facility handling costs and internal transportation costs. While this could suggest that no hubs are needed in the network, we find that the hubs are necessary to enable the realization of direct shipping cost benefits. By holding the network safety stock at hubs, the requirement for holding safety stock at the DCs is lowered. Thus, transportation cost savings may be realized, while not adding the burden of increased inventory at the DCs. Without hubs to hold safety stock, we find that a pure direct shipping strategy is an expensive and risky strategy. We discuss safety stock allocations and a pure direct shipping model later in our report.

Figure 10

Category Cost Comparison for Current State vs. Baseline Optimized Models



This model becomes our baseline for comparing against other scenarios and is referred to as the baseline model throughout the remainder of this report. By comparing all other scenarios to the 2_BaseOpt model, we can isolate the cost differential associated with sourcing decisions or network configuration changes without considering the cost savings associated with making all lanes available and allowing the nearshore supplier to produce all products.

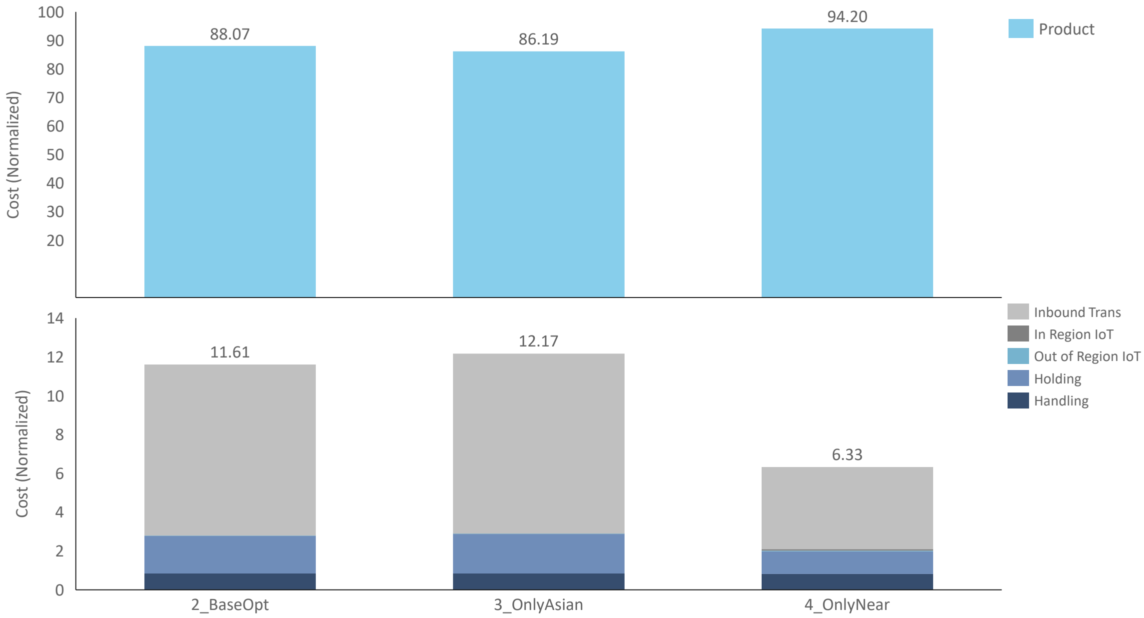
All Nearshore vs. All Asian Sourcing. We execute two scenarios to quantify the impacts of a single-source, location-specific network. Scenario 3_OnlyAsian removes the nearshore supplier from the network, and scenario 4_OnlyNear removes the Asian supplier from the network.

To determine whether the current supplier minimums are optimal and to quantify the costs associated with consistent ordering patterns, we run a scenario in which both suppliers are available but neither has a minimum production requirement. Scenario 6_NoSupMin removes the minimum production requirement from the model. Suppliers can produce up to their maximum capacity each time period but do not have a hard requirement to produce any product.

We find that across all scenario models where a minimum supplier production requirement exists, the nearshore supplier does not produce more than the minimum requirement. The nearshore supplier only producing the minimum in these scenarios, suggests that, from a cost perspective, the reduced transportation and inventory costs do not justify the higher production cost by sourcing closer to the U.S. Figure 11 shows the cost differential between the baseline model and scenarios 3_OnlyAsian, 4_OnlyNear, and 6_NoSupMin.

We find approximately a 50% reduction in total transportation costs when sourcing from

Figure 11
Category Cost Comparison for Sourcing All Nearshore vs. All Asia



nearshore suppliers compared to Asia. Given the lower variability in lead times, inventory costs are reduced by 43% when sourcing nearshore due to the reduced requirement for overall safety stock in the network. A pure nearshore sourcing strategy results in 44% less safety stock in the network.

Still, the benefit of the per-unit purchasing cost of products from Asia is greater than the transportation and inventory cost savings gained from nearshore sourcing. Product costs from the nearshore supplier are 15 to 20% higher than in Asia, depending on the product family. Since the product cost drives approximately 92% of the total cost, sourcing from Asia remains cheaper overall.

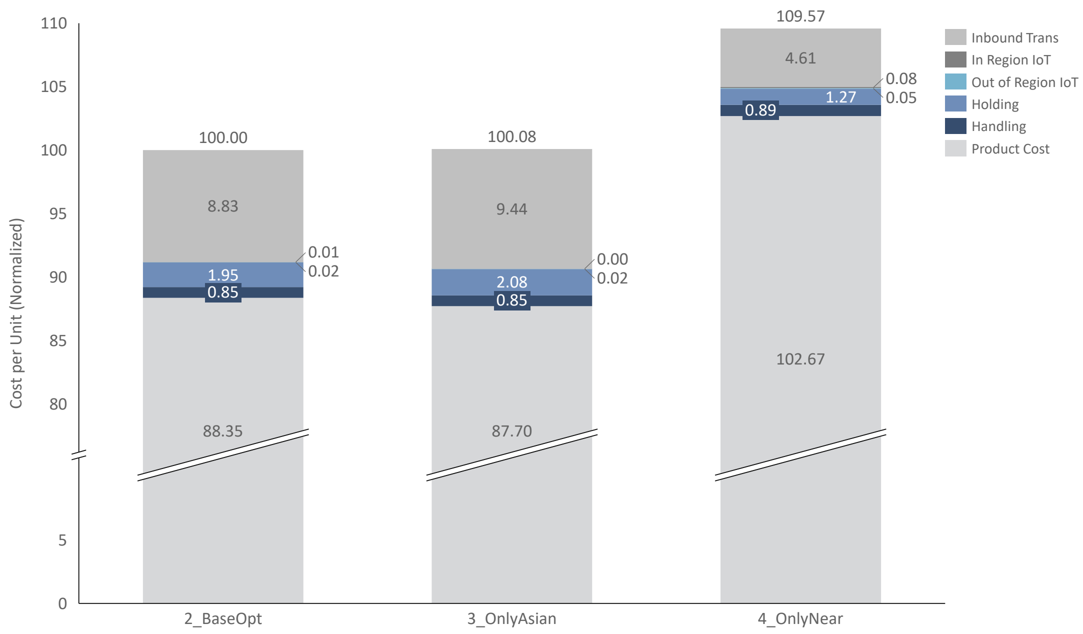
In scenarios with required production from the nearshore supplier, we find that product A, the cheapest product family, is produced, with more expensive products, where the per unit product cost differential is greater, are sourced from Asia. There is sufficient demand within the network such that the demand for product A exceeds the minimum production requirement for the nearshore supplier, so the model is never forced to produce another product to meet the minimum production requirement.

Removing the supplier minimum in scenario 6_NoSupMin provides results similar to scenario 3_OnlyAsian. When the supplier minimum is removed, the nearshore supplier is not utilized. Since demand exceeds the supplier's minimum production capacity, order volumes from Asia do not change significantly.

While the results presented provide total annual costs, they do not fully represent the cost associated with a nearshore sourcing strategy. Since less inventory is held when sourcing from nearshore suppliers, the order volumes vary based on sourcing strategy. We find that a pure nearshore strategy leads to a decrease in total order volume by approximately 7%. Thus, the cost differential associated with purely ordering less must be accounted for. We divide the costs associated with each scenario by the number of units purchased in the scenario. We then determine the per unit cost, by cost category, for purchasing one unit of inventory. Figure 12 provides the cost per unit details after normalizing for order volumes.

Figure 12

Category Per Unit Cost Comparison After Normalizing for Order Volumes



We find a 14.3% increase in purchasing cost per unit while we find a 50% reduction in per unit costs for inbound transportation and holding. Still, given the significance of product costs in total costs, the increase in purchasing costs outweighs the benefits gained.

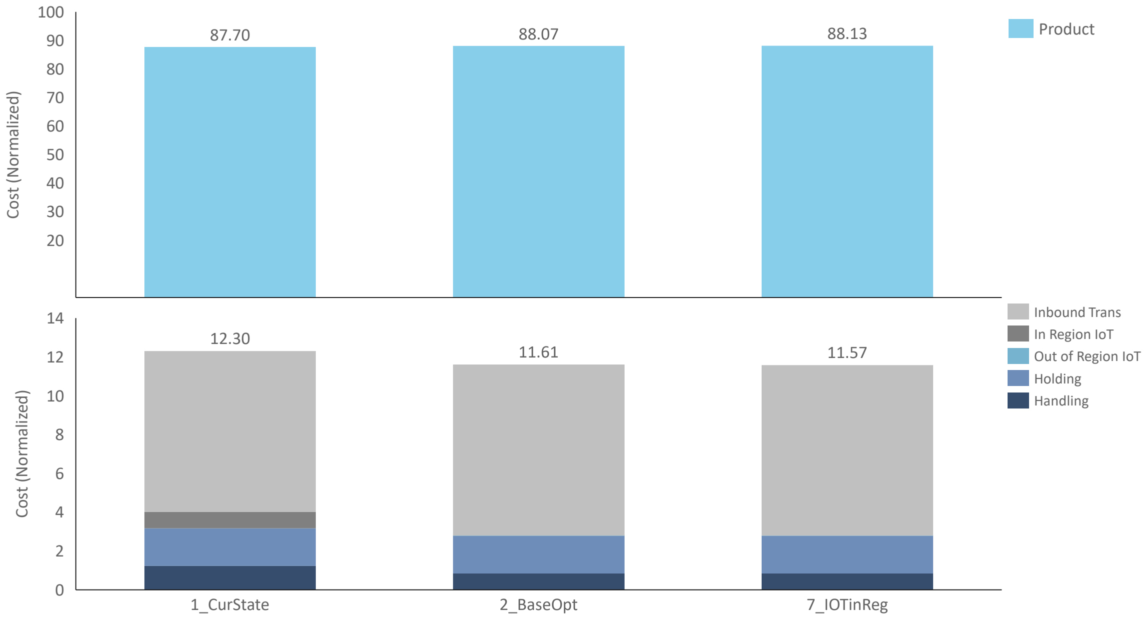
These findings help to quantify the risk mitigation premium associated with sourcing from a nearshore supplier. We find a $9.49 per unit cost premium in the 4_OnlyNear model compared to a pure Asian sourcing strategy in the 3_OnlyAsian model, or approximately a 10% cost increase.

Available Shipping Lanes. We seek to identify the optimal IoT lanes within the network. We consider two scenarios in which both scenarios allow for direct shipping from the supplier to all TSI facilities. Scenario 2_BaseOpt allows for shipping between each hub and all distribution centers. Scenario 7_IoTinReg allows for only hub to DC connections between hubs and DCs in the same region (West, Central, and East).

As mentioned previously, 2_BaseOpt finds cost savings compared to the 1_CurState model by allowing for direct shipping to DCs. Now, comparing 2_BaseOpt and 7_IoTinRegion, we find minimal cost savings of .03% associated with allowing internal transfers between hubs and DCs out of the hubs current service region. Figure 13 illustrates the relative cost differences.

Figure 13

Category Cost Comparison for Variations in Available Shipping Lanes



While the total cost savings associated with shipping between hubs and DCs across regions are minimal, the lane level volumes shipped between hubs and DCs do change. We find that the Eastern hub ships significant volume to Central region DCs. Similarly, the Western hub ships a fairly large volume to a Central DC.

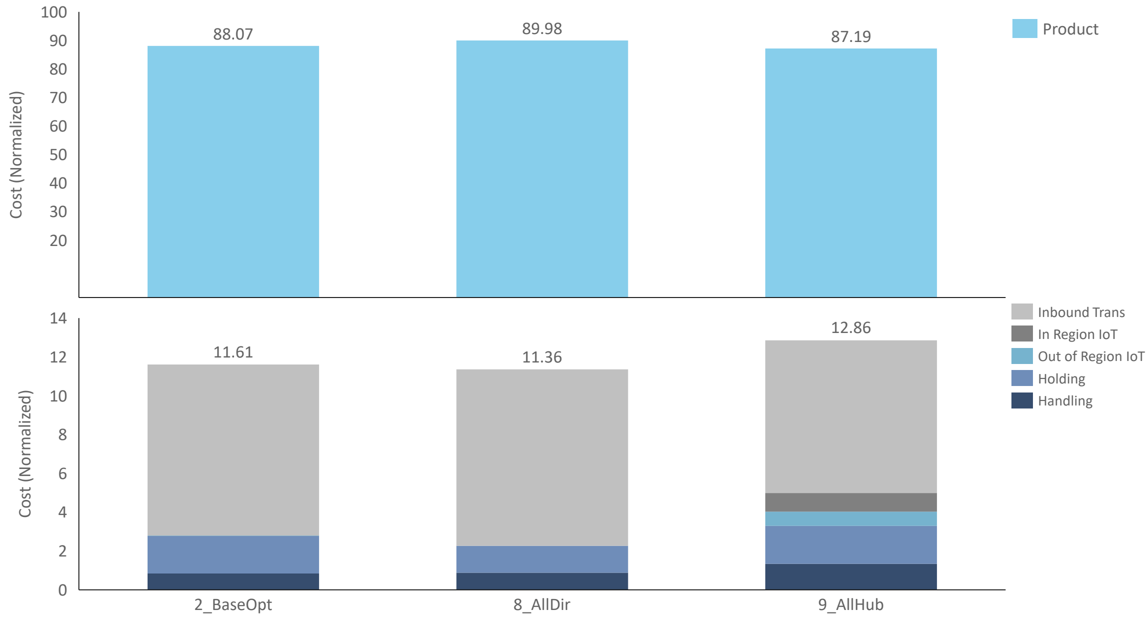
All Hub-and-Spoke vs. All Direct-to-DC. We execute two scenarios to quantify the impacts of a pure Direct-to-DC (8_AllDir) and pure Hub-and-Spoke (9_AllHub) distribution strategy. Scenario 8_AllDir removes the hubs from the network, forcing the supplier to ship directly to the distribution centers. Safety stock inventory is held at the DCs in this model. Scenario 9_AllHub does not allow the supplier to ship directly to the distribution centers; all units are shipped from supplier to hub, then hub to DC.

Both Direct-to-DC and Hub-and-Spoke exclusively are more expensive than the baseline model (2_BaseOpt). The pure Direct-to-DC model is 1.7% more expensive while the pure Hub-and-Spoke is a marginal .4% more expensive compared to the baseline model. Figure 14 provides the relative cost differences.

A Direct-to-DC model provides transportation cost savings compared to the Hub-and-Spoke model. Additionally, this network configuration provides inventory cost savings as inventory and cycle stock are held directly at the DCs with no additional inventory held at hubs. Note that we do not increase safety stock levels at the DCs to accommodate for the removal of stock at the hubs, although in operations this must be considered. Nevertheless, the overall cost of the Direct-to-DC model is more expensive than the Hub-and-Spoke model due to the 3% increase in total product purchasing costs. The increase in total product costs is associated with the 2.5% increase in overall product volume ordered in the Direct-to-DC model compared

Figure 14

Category Cost Comparison for Shipping All Direct vs. All Through a Hub



to the Hub-and-Spoke model. When orders are placed with suppliers, the model seeks to completely fill loads with product, even if the SKU is not needed immediately, given the flat cost associated with the load. When full loads are shipped to hubs, the hubs can reallocate the required product SKUs to multiple DCs, whereas shipping full directly to DCs results in the product being shipped even when it is not needed immediately to realize the benefits of load consolidation.

Requiring the model to adhere to only one strategy, whether all direct or all through a hub, increases the total cost compared to the baseline model. Forcing every unit to go through a hub incurs a marginal cost increase compared to the baseline model. Shipping all products directly to DCs increases the overall cost by 1.5%. These findings suggest that a hybrid approach of Direct-to-DC shipping to realize transportation cost benefits while leveraging the Hub-and-Spoke network to hold safety stock and manage demand spikes is optimal.

Safety Stock Reallocation. We execute a scenario to quantify the impact of holding safety stock at DCs versus hubs. Scenario 10_DC requires DCs to hold safety stock based on the product and DC target day of supply levels that TSI uses in current operations. Given each product/DCs combination, we determine the unit safety stock requirement based on the average daily demand multiplied by the days of supply target. The hubs safety stock requirement is lowered to account for the additional inventory held at the DCs. The total safety stock in the network increases in this scenario compared to scenario 2_BaseOpt, in which only hubs have hard safety stock constraints.

Inventory and transportation costs increase (1.2% and 3.8% respectively) in scenario 10_DCSafety compared to scenario 2_BaseOpt. Product purchasing cost increases by 1.6%, a substantial amount given the significance of product cost in total costs. Similar to the discussion on the all-direct model, this is a result of the incentive to ship full supplier loads. Even when specific product SKUs are not needed, the model may order the product to ship full loads from the supplier. This leads to an increase in the overall volume ordered from suppliers. Figure 15 shows the cost differential by category between scenario 10_DCSafety and the baseline model 2_BaseOpt.

Figure 15

Category Cost Comparison for Hub vs. DC Safety Stock Allocation

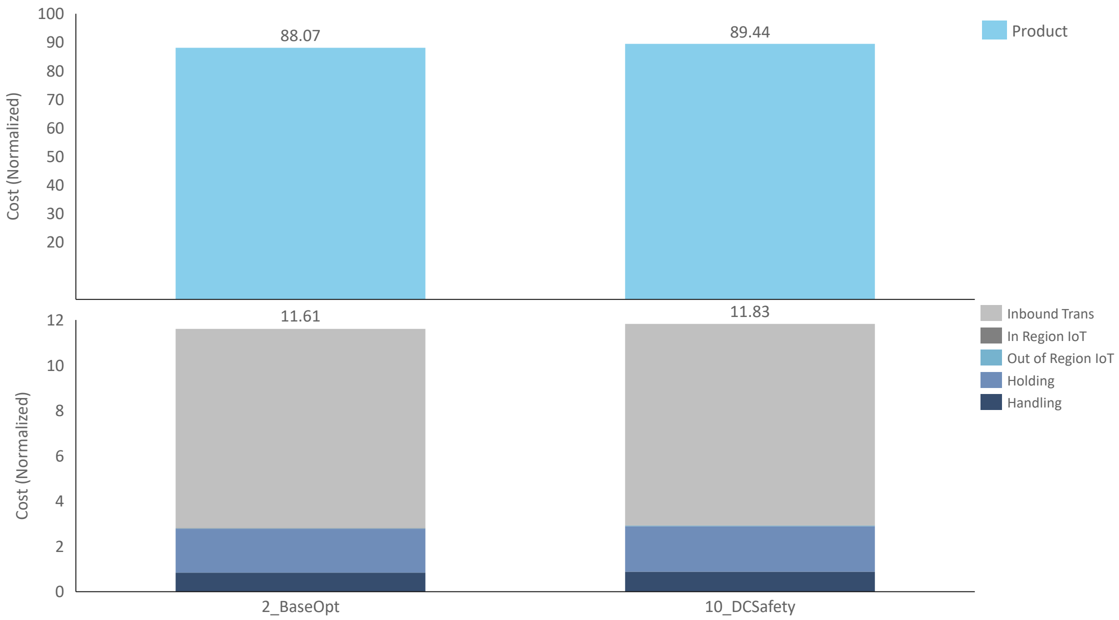
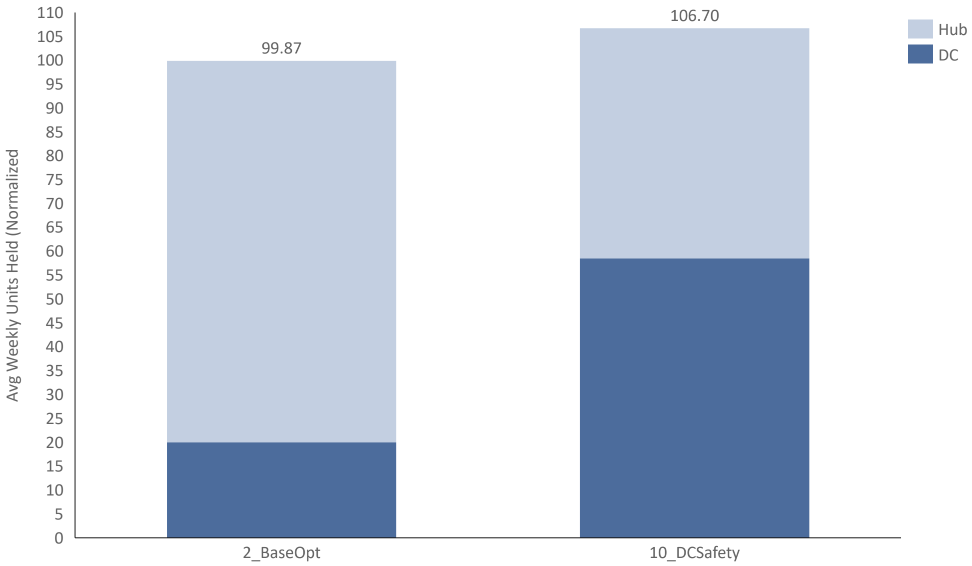


Figure 16 shows the difference in the average inventory held each time period between the two models. We see that the allocation of inventory moves from approximately 80/20% between the hubs and DCs in the 2_BaseOpt scenario to approximately 45/55% in the 10_DCSafety scenario.

Figure 16
Average Weekly Units Held at Hubs and DCs

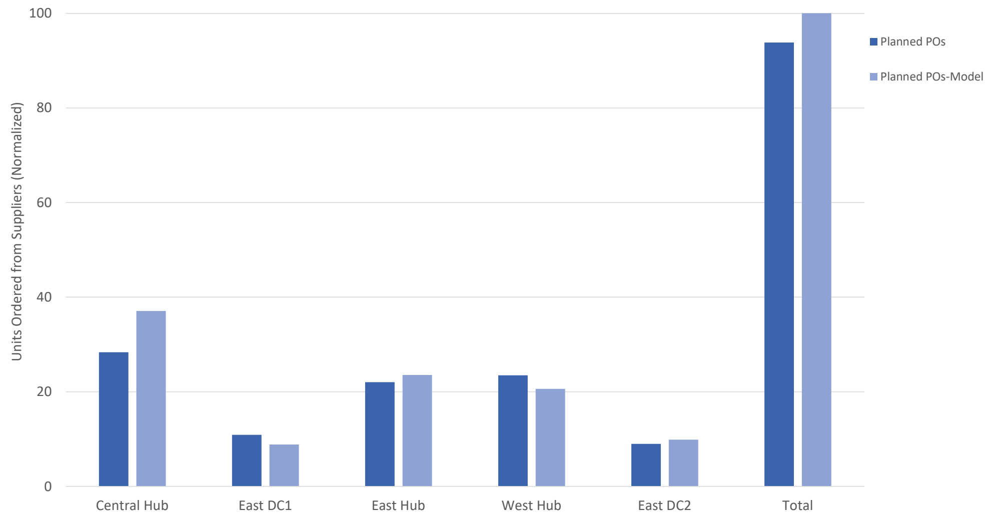


5.2 Forward Looking Model Results

The comparison presented in Figure 17 illustrates TSI's planned Purchase Orders (PO) over a 52-week period using the Forward Looking Model. For the purposes of data confidentiality, all numerical values have been normalized by setting the model's total planned POs to 100. The results show that the model mirrors the trends of TSI's current operational system, maintaining similar order quantities from suppliers at each hub and East DCs. However, since the model does not allow for shipments transfer between DCs, all shipments must pass through hubs to reach the DCs. Consequently, the model suggests that hubs should order more quantity from suppliers to minimize the need for shipments between DCs and to avoid unexpected costs. In contrast, TSI's operational system allows for more flexible delivery routes between DCs. As a result, the model predicts higher planned order quantities in total compared to TSI's current ordering system. This discrepancy shows the opportunity for TSI to examine potential optimized planning patterns suggested by the Forward Looking Model.

Moreover, the Forward Looking Model serves as a strategic tool for TSI to reference when considering updates to their current supply chain operations. For instance, modifications such as updating supplier capacity requirements, extending supplier maximum capacities, adjusting product costs, revising transportation rates, or adding new lanes and facilities are all integrated into the model. This allows for a comprehensive simulation of potential changes and their impacts on the supply chain network. Adjustments in ordering patterns between Asian and nearshore suppliers, purchase quantities at each facility, and shipment transfers can be assessed through the model, providing TSI with clearer visibility of the effects these alterations may have. Figure 18 illustrates the potential ordering patterns at each facility if TSI

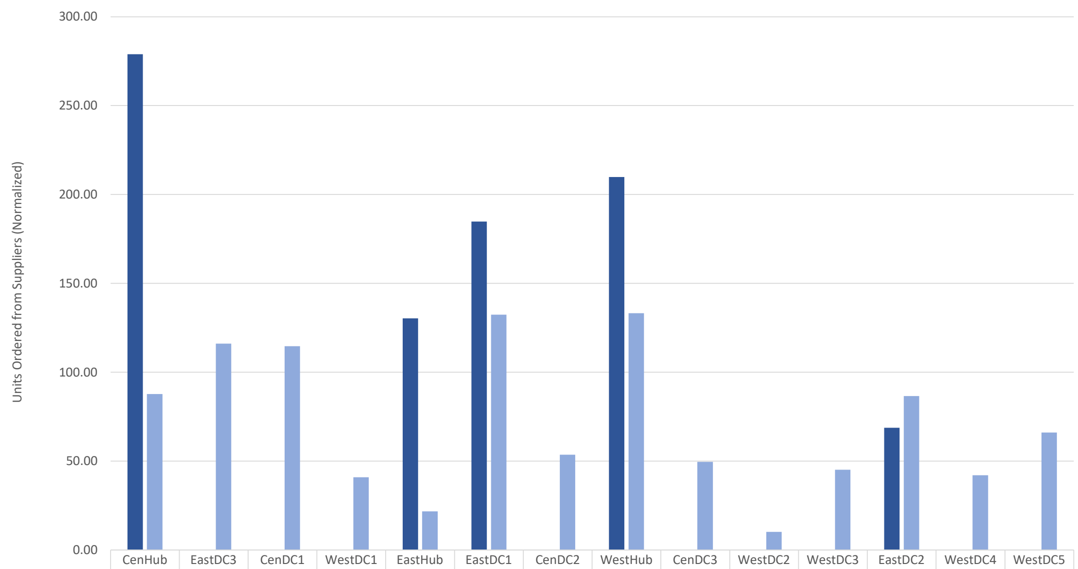
Figure 17
Planned PO Quantity Comparison within 52 Weeks



were to open all lanes between suppliers and facilities, compared to the current operations. Additionally, Figure 18 demonstrates one of the findings in Section 5.1.3, in which the model ships less quantity through the Central hub, indicating that the Central region DCs are fed by other hubs. The result potentially allows TSI to reevaluate the strategy of the Central hub or reallocate resources for other product families.

Overall, the agility of the Forward Looking Model makes it a reflective tool for TSI to evaluate new policies or mitigate potential risks in future supply chain strategies and create a more resilient supply chain network.

Figure 18
Open All Lanes Between Suppliers and Facilities



	CenHub	EastDC3	CenDC1	WestDC1	EastHub	EastDC1	CenDC2	WestHub	CenDC3	WestDC2	WestDC3	EastDC2	WestDC4	WestDC5
Sum of Planned POs	278.85	0.00	0.00	0.00	130.34	184.76	0.00	209.78	0.00	0.00	0.00	68.75	0.00	0.00
Sum of Planned POs (Model)	87.71	116.08	114.65	40.99	21.74	132.41	53.62	133.19	49.59	10.18	45.18	86.57	42.03	66.06

Sum of Planned POs   Sum of Planned POs (Model)

5.3 Managerial Insights and Recommendations

In this section, we discuss insights for managers and provide recommendations to our sponsor company. We provide insights into the quantitative results while also considering non-quantitative factors that were not included in our model, like service and supply resiliency.

The recommendations include:

- Assess allocation of safety stock between hubs and DC
- Further develop the nearshore supplier to increase cost-competitiveness
- Leverage a hybrid distribution strategy by increasing direct shipping
- Allow for additional hub to DC lane connections

Assess allocation of safety stock between hubs and DC. We recommend allocating a greater amount of safety stock to the hubs and reducing the amount of inventory held at the DCs.

The centralization of inventory at the hubs provides agility, increasing customer service while also saving on transportation and inventory holding costs. Given the hubs can replenish DCs significantly faster (1 week) than suppliers (4 to 13 weeks), holding safety stock at the hubs allows for a quicker response to fluctuations in demand without having to ship unplanned loads between DCs.

Additionally, cost savings can be realized by reducing total safety stock in the network. When demand is aggregated to the network level to determine safety stock requirements, the overall safety stock requirement can be decreased given risk pooling.

Further develop the nearshore supplier to increase cost-competitiveness. A significant contribution of our model is the quantification of the total cost of nearshore sourcing. Sourcing from nearshore suppliers provides qualitative benefits such as responsiveness to demand due to shorter overall lead times and resiliency against changing regulations. Our model identifies the total landed cost per unit of choosing to source from nearshore. TSI is now able to make more informed strategic decisions given a more robust picture of the cost, service, and resiliency trade-off.

Prior to our project. TSI could not quantify the total cost of operations with their nearshore supplier. With the development of our model, they now have insights into the trade-offs between inventory, transportation, and product cost. We find that while production in Asia is still more cost-effective, the cost differential is less significant when inbound transportation costs and reduced inventory requirements are considered.

Given shorter lead times and lower variability in the planned lead time from nearshore supply, sourcing closer to customers provides an avenue for more quickly responding to changes in consumer demand. Having a supplier close to customers lowers response time to demand fluctuations. Additionally, TSI has a hedge against global disruptions, a strategic advantage given the increased complexities of today's supply chains. Our model quantifies how much more it costs to maintain this flexibility.

Equipped with data on the quantification of nearshore supplier operations, TSI can improve its strategic decision-making related to its sourcing strategies. While a cost premium remains in sourcing from nearshore, the non-quantified benefits in resiliency and responsiveness to demand make the decision to invest in nearshore capabilities more attractive.

To achieve further resiliency while remaining cost-conscious, we recommend that TSI continue to work with the nearshore supplier to develop its capability and lower production costs. The large product cost difference is the greatest driver for purchasing from Asia rather than nearshore. As the product cost becomes more competitive, the decision becomes more attractive to source from nearshore.

Leverage a hybrid distribution strategy by increasing direct shipping. We find an opportunity for TSI to increase its direct shipping to specific DCs. For cycle stock, direct shipping is the most cost-effective. To respond to unforeseen demand spikes and late orders from suppliers, we recommend utilizing the Hub-and-Spoke distribution strategy, which requires holding safety stock at the hubs. Holding inventory at the hubs also allows for aggregation of demand when determining safety stock. Thus, less safety stock is required in the network, as discussed previously.

A hybrid network design utilizing the Direct-to-DC model for cycle stock and the Hub-and-Spoke network for demand fluctuations provides the most cost-effective, resilient network. We find that the largest opportunity for direct shipping is from Asia to the West Coast DCs, while continuing to ship through the Hub-and-Spoke network for DCs in the Central region of the country.

Allow for additional hub to DC lane connections. Our model consistently ships units between the hub in the East to DCs in the Central region of the country. While there are savings associated with this strategy, the savings are marginal. Still, the identification that Eastern or Central hubs can service Central DCs at similar costs creates flexibility in TSIs network. If costs are similar between multiple hubs to a DC, TSI may consider how excess capacity between the hubs may be used for other products. For example, if the Central region DCs are serviced from the Eastern hub, this frees up capacity at the Central hub for other products.

Additional Insights. Our project's main contribution is a tool to quantify the total supply chain costs associated with various network design and sourcing decisions. While our model does identify opportunities for cost savings, many of the savings are relatively small compared to current operations. Still, quantifying costs related to the various design decisions provides important insights. While TSI may not appreciate significant cost savings solely from our recommendations, the insights associated with understanding total costs allow them to consider other network strategies, and to validate that some network changes may not be worth the investment.

6 Conclusion

6.1 Project Summary

Our sponsor company, Tempur Sealy International, has traditionally sourced most of its adjustable base product category from Asia. The product was shipped directly to its distribution centers and then to various retail stores. Given the long and variable lead times from Asia and significant demand fluctuations, TSI has made strategic investments nearshore supply capabilities along with opening centralized hub facilities to fulfill demand via a Hub-and-Spoke model. Given these investments, TSI sought to determine the optimal supply chain distribution network. They wanted to understand how much, of what product, should be sourced from where, and how the product should flow through the network.

Our project provides a quantitative method for analyzing various sourcing and network configuration scenarios within TSI's distribution network. We identify the optimal network design considering both cost and service, including supplier sourcing mix, replenishment strategy, and network flow paths.

To accomplish this goal, we formulate and build a mixed integer linear program. We optimize to minimize total costs across product purchasing, transportation, handling, and holding costs. Our model decides how much to order from each supplier, how much to ship between hubs and DCs, and how much inventory to hold at each facility. We model demand across a 52-week period to understand supplier lead time implications and responsiveness to demand fluctuations.

To quantify the cost impact of supplier sourcing and network configuration decisions, we ran a Monte Carlo simulation across 10 model scenarios. To ensure the robustness of our solution, we ran each model against 25 demand realization instances, each consisting of 52 weeks of demand.

Our results quantify the cost increase associated with nearshore sourcing. The quantification of the total landed costs, including lower transportation and inventory holding costs but with higher product costs, allows for a more informed strategic sourcing strategy.

In addition to quantifying the impact of different network designs, we find cost saving opportunities through the reallocation of safety stock between DCs and hubs and for increased direct shipping of cycle stock to DCs.

The contribution to TSI includes a method for quantifying the cost impacts between purchasing, replenishment, and inventory management decisions at both the strategic and tactical level. Our model provides a reference for TSI when evaluating potential updates to their existing supply chain operations, allowing for comparisons with their current operational model. With this model, TSI gains insight into the impact of various scenarios, both in the long and short term, on current operational, enabling them with an analytical method to support their decision making process.

6.2 Future Research

Our model provides a usable quantitative method for ongoing scenario analysis as TSI's network continues to evolve. We identify future research opportunities for further development of our model and considerations in TSI's operations given our findings.

First, given the scope of our project, we did not consider stochasticity or variability in input data (specifically demand and lead times). Future research may seek to incorporate supplier lead time and demand variability into the model. Second, future studies may formulate additional scenarios that consider various cost structures for the nearshore supplier to determine the cost reduction required for competitiveness with the Asian supplier, given the benefits of higher service and shorter lead times. The model may also be expanded to other product families. Finally, given our identification of an opportunity for a reduction in overall safety stock, future research may perform deeper analysis to determine optimal inventory and safety stock policies.

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