Sustainable Network Design of Perishable Foods

by

Maria Anna Tartaglia

and

Yin Miki Wang

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

June 2023

Signature of Author: ____
Department of Supply Chain Management
May 12, 2023

Signature of Author: ____
Department of Supply Chain Management
May 12, 2023

Certified by: ____
Dr. Josué C. Velázquez Martínez
Director, MIT Sustainable Supply Chain Lab
Capstone Advisor

Certified by: ____
Fabio Castro
PhD Student
Capstone Co-Advisor

Accepted by: ____
Prof. Yossi Sheffi
Director, Center for Transportation and Logistics
Elisha Gray II Professor of Engineering Systems
Professor, Civil and Environmental Engineering

Sustainable Network Design of Perishable Foods

by

Maria Anna Tartaglia

and

Yin Miki Wang

Submitted to the Program in Supply Chain Management
on May 12, 2023 in Partial Fulfillment of the
Requirements for the Degree of Master of Applied Science or Master in Supply Chain Management

ABSTRACT

Our project analyzes the trade-offs between costs, service level, inventory strategy, and CO_2 emissions in a global food and beverage retailer's current network design. We analyze the network design of a perishable product and evaluate which levers or variables can change (transportation mode, suppliers' locations, inventory) in their existing network, as well as what variables are constraints and cannot be changed (truck sizes, product specifications, DC locations). We explore how full truckload vs. less-than-truckload transportation impacts their network and consider new supplier locations. We create a network design model in Python that offers the sponsor company various solutions that highlight the trade-offs between costs, service level, and CO_2 emissions. Key insights of this project are the following: (1) the company should utilize LTL transportation; (2) there is a cost benefit of adding a third supplier to the network design; (3) if the company wants to achieve a higher service level, the total costs of inventory, transportation, and COGS will be higher in comparison to the total costs of a lower service level; and (4) for each service level, as the cost decreases the total emissions (kg CO_2) per week and expected number of expired items also increases.

Capstone Advisor: Dr. Josué C. Velázquez Martínez

Title: Director, MIT Sustainable Supply Chain Lab

Capstone Co-Advisor: Fabio Castro

Title: PhD Student

ACKNOWLEDGMENTS

We would like to give a special thank you to Fabio Castro for his tremendous efforts in providing guidance on this project. He selflessly dedicated countless hours to helping us code and create strategies on how to execute this project. Fabio is among the brightest at MIT's Center of Transportation and Logistics. We wish him the best in completing his PhD program and know he will accomplish great achievements in the future. Thank you, Fabio!

Thank you to Josue for his continued support in advising our project and helping shape the strategy of our methodology and execution of the capstone.

Lastly, thank you again to our sponsor company for their support and commitment to partnering with us to make this capstone project successful. We have enjoyed working with the team and hope this project can provide powerful insights to help the business grow and succeed.

Table of Contents

List of Figures ... 6
List of Tables ... 7
Chapter 1: Introduction ... 8
1.1 Motivation ... 8
1.2 Sponsor Company Background ... 9
1.3 Research Question ... 12
1.4 Project Flow ... 12
Chapter 2: State of the Art ... 14
2.1 Challenges with Perishable Food Supply Chains ... 14
2.2 Environmental Impact and Waste ... 15
2.3 Common Methodologies for Network Design ... 16
2.4 Model Selection ... 18
Chapter 3: Methodology ... 19
3.1 System Specification ... 19
3.2 Model Scenarios ... 22
3.3 Model Formulation ... 23
3.3.1 Inventory Policy Formulation ... 23
3.3.2 Expiration Formulation ... 25
3.3.3 Emissions Formulation ... 29
3.3.4 Optimization Formulation ... 30
Chapter 4: Results and Analysis ... 33
4.1 Initial Findings ... 33
4.2 Scenario 1: Matrix with 11 Scenarios with Number of Suppliers Open: Transportation Cost ... 35
4.3 Scenario 1.1: Matrix with 11 Scenarios with Number of Supplier Open Excluding Supplier 0 - Transportation Cost ... 40
4.4 Scenario 2: Matrix with 11 Scenarios with Number of Supplier - Transportation Cost and COGS ... 41
4.5 Scenario 3: Matrix with 11 Scenarios with Number of Supplier - Transportation Cost and Inventory Cost ... 43

4.6 Scenario 4: Matrix with 11 Scenarios with Number of Supplier Open Excluding Supplier 0 - Transportation Cost and Inventory Cost 46
4.7 Scenario 5: Matrix with 11 Scenarios with Number of Supplier - Transportation Cost, COGS, and Inventory Cost 47
4.8 Scenario 6: Impact to Costs and Service Level with COGS 49
4.9 Scenario 7: Impact to Costs and Service Level with COGS with Longer Reorder Period 51
4.10 Scenario 8: Costs and Expired Items by Service Level 52
4.11 Scenario 9: Costs and Emissions by Service Level 54
Chapter 5: Discussion 56
5.1 FTL vs. LTL Transit Times 56
5.2 Cost of Adding Additional Suppliers 56
5.3 Excluding Supplier 0 57
5.4 Considering COGS into Model 57
5.5 Trade-offs with Expired Items 58
5.6 Trade-offs with Emissions 58
Chapter 6: Conclusion 60
References 62
Appendix 64

List of Figures

Figure 1: Network Design Conceptual Model

Figure 2: Project Flow

Figure 3: Lead Time Assumptions for Expiration of Product A

Figure 4: Periodic Review (R,S) Graph

Figure 5: Distribution Graph for the Probability of Products Expired

Figure 6: Graph of Number Items Expired in Order Cycle

Figure 7: LTL Cost Per Unit Graphs

Figure 8: Graph of FTL Cost Per Shipment

Figure 9: Transit Times (LTL vs. FTL) Graphs

Figure 10: Visual Representation of Shipment Routes for 3 Suppliers

Figure 11: Chart of Costs for Opening Additional Suppliers

Figure 12: Chart of Costs for Opening Additional Suppliers with COGS

Figure 13: Chart of Costs for Opening Additional Suppliers – Transportation and Inventory

Figure 14: Transportation and Inventory Costs by Service Level

Figure 15: Transportation and Inventory Costs + COGS by Service Level

Figure 16: Transportation and Inventory Costs + COGS by Service Level with 2 Week Reorder Period

Figure 17: Total Cost and Number of Expected Expired Items Per Week by Service Level

Figure 18: Total Cost and Emissions Per Week by Service Level

List of Tables

Table 1: Tools and Reference Applied in Supply Chain Network Design

Table 2: Supplier Capacity in Units Per Week

Table 3: Expiration Variables

Table 4: Parameter Variable Description

Table 5: Decision Variable Description

Table 6: Recommended Supplier Locations Based on Number of Suppliers in Operation

Table 7: Total Transportation Cost for Three Suppliers in Operation

Table 8: Recommended Supplier Locations Excluding Supplier 0

Table 9: Recommended Supplier Locations with COGS

Table 10: Recommended Supplier Locations with Transportation and Inventory Costs

Table 11: Recommended Supplier Locations and Transportation Modes with Maximum of Three Suppliers – Transportation and Inventory Costs

Table 12: Recommended Supplier Locations Excluding Supplier 0 – Transportation and Inventory

Table 13: Recommended Supplier Locations - Transportation Cost, COGS, and Inventory Cost

Table 14: Recommended Supplier Locations and Transportation Modes with Maximum of Three Suppliers – Transportation, Inventory Costs, and COGS

Chapter 1: Introduction

In this chapter, we introduce our capstone project and the sponsor company. We review the topic of network design and supply chain complexities, the relationship of total costs and carbon emissions, and the motivation and background of the project. Finally, we discuss the project flow and outline key milestones on how we execute the project.

1.1 Motivation

The network design of a business is planning and mapping out the infrastructure for a company. A company's network design includes identifying the location of suppliers, distribution centers, and retail stores. As the network of a business expands, the complexities of the supply chain increase as well. Many companies want to focus on cost minimization of their network design while also considering environmental impact.

Companies have to determine the trade-offs between total cost and carbon emissions of their network design. A network with the lowest cost is most likely not going to minimize carbon emissions in parallel. The mode of transportation a company uses such as less-than-truckload or full truckload transportation impacts costs and carbon emissions. A company has to decide what are their priorities in regards to costs and environmental impact since these two factors are often working against each other.

There are increased complexities in a company's network design when perishable products are involved. Fresh foods are more perishable, which creates supply chain challenges for companies that distribute products with a shorter shelf life. The Cold Chain Group researched perishable food supply chains and discovered 30% of perishable foods arrived at their retail destination spoiled (Woods, 2015). Companies have to do extra planning to make sure the shelf life of a food product is accounted for in their distribution network planning.

In this paper, we analyze the network design of a global food and beverage retailer for a new perishable product. We explore the tradeoffs of costs, carbon emissions, and number of expired products in their network design. In Section 1.2, we discuss the background of our sponsor company.

1.2 Sponsor Company Background

The sponsor company referenced as Company X is a well-known brand in the beverage and food industry. Although Company X is primarily a beverage company, they offer food products to pair with their drinks. In this capstone project, we analyze a new part of Company X’s food business that sells pre-packaged perishable food offerings. This product is defined as Product A.

Product A is a small food package that has an assortment of fruits, cheeses, cold cut meats, nuts, and other snacks. Product A is a new type of pre-packaged food container compared to an already existing item, Product B. The main difference between Product A and Product B is the shelf life. Product B is prepared and packed in sites close to Company X’s retail stores, delivered daily and has a shelf life of 72 hours. Product A has a longer shelf life of 70 days. This development allows Company X to serve the markets where daily delivery or proximity to a Product B production site is not a practical option.

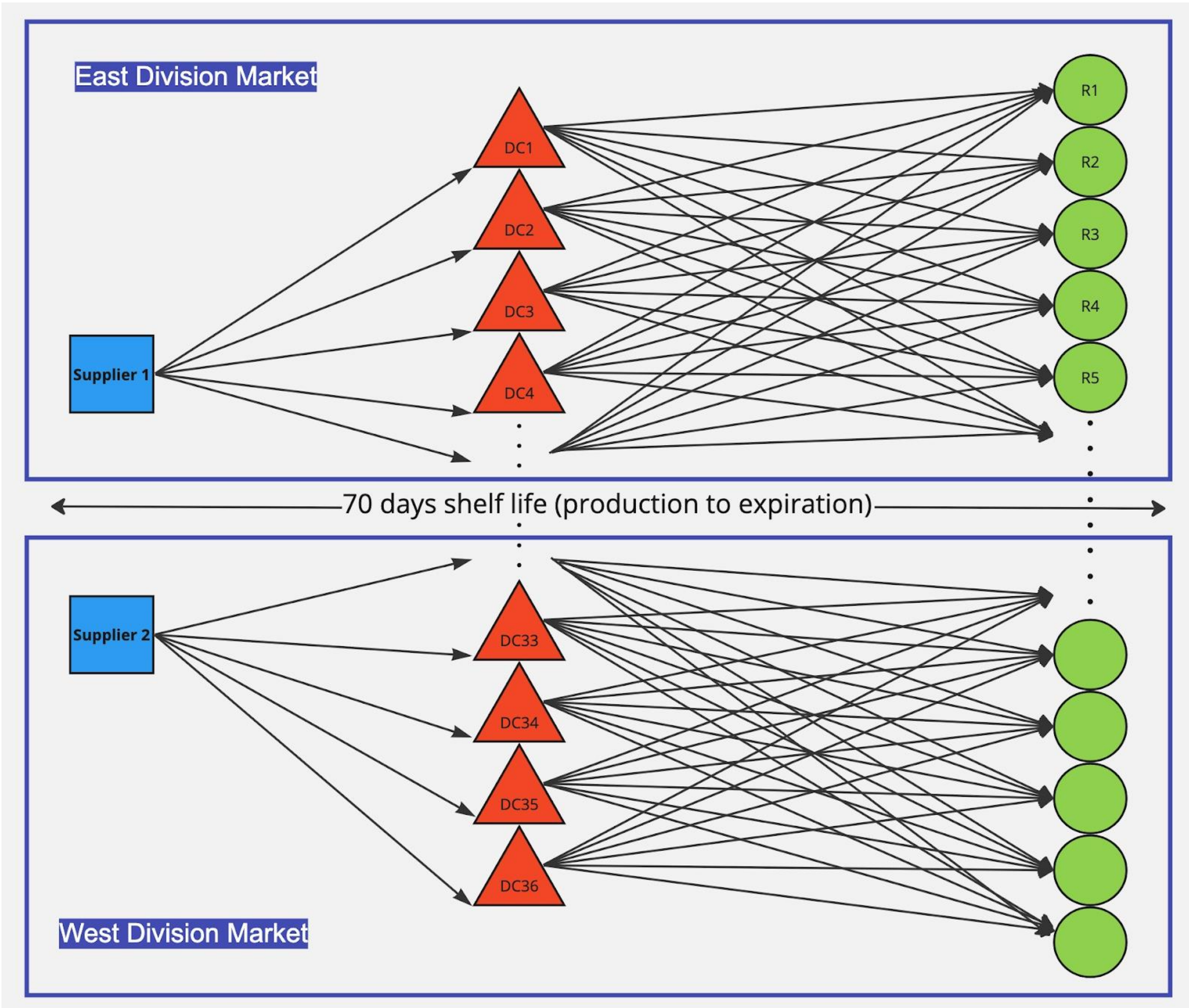
Product A was launched in June 2021, so there is currently limited data available in late 2022 when this project was initiated. Since this is a new product, the demand is uncertain, which makes it difficult for the planning team to predict how much inventory they need to supply their distribution centers and retail stores. Due to the variability in demand, this product category is experiencing a service level of 90%, which is below the target of 98.5%. The irregular demand has made it difficult to achieve their service-level targets. If there is a difference between the predicted demand vs. the actual demand, there may not be inventory in the right place at the right time, which decreases service level.

Company X wants to explore how to improve the overall supply chain for Product A due to the fast growth of this product portfolio. From 2021 to 2022, Company X has seen double digit-growth in the food category compared to other segments of the business. There is an interest to explore ways to increase margins, improve the service levels, and reduce the amount of waste from expired products. Company X wants to explore whether their current network design can more efficiently allocate their resources to distribute Product A and increase profit margins.

Company X has two current food suppliers for Product A. There are 34 distribution centers that supply the individual stores (**Figure 1**). Depending on proximity to the food suppliers and distribution centers, each store offers either Product A or Product B. An important element of the distribution network is that the food products need to be refrigerated, which limits where the food items can be stocked and who can deliver the items. Company X sells other food items that are frozen across the supply chain which have a shelf life of four to nine months. Product A has a shorter shelf life compared to their frozen food offerings, so it has a different network design.

Figure 1

Network Design Conceptual Model



Note. **Figure 1** shows the current network design for the sponsor company. There is an East and West Division where suppliers ship to DCs and DCs ship to retail stores. Product A has a total shelf life of 70 days.

When Product A initially launched, Company X planned to ship this product by less-than-truckload transportation. This means that a small number of pallets can be shipped on a truck that is also delivering for other suppliers, which drives down the transportation costs. LTL shipments were incurring high lead times which led to high product expiration rate. Our sponsor company is currently shipping by full truckload, which is the fastest delivery option to mitigate the product expiring before it gets to the DCs. Each shipment does not always fill up the whole truck, but Company X is still paying the full amount to utilize the truck exclusively for their deliveries and services.

1.3 Research Question

In this study, we analyze the supply chain of Product A by evaluating transportation methods, service levels, and costs. The goal is to propose strategy plans that optimize the physical flow of the products while increasing profit margin and service level and also minimizing environmental impact.

A network design model in Python offers Company X various solutions that highlight the trade-offs between costs, service level, and CO_2 emissions. The model helps us define what levers or variables can change in their existing network (transportation mode, supplier location, inventory), as well as what variables are constraints and cannot be changed (truck sizes, product specifications, DC locations). Our hypothesis is the following: in order to achieve higher service levels, total costs and CO_2 emissions will increase, as well as number of expired units.

1.4 Project Flow

Our project plan has 5 key steps that outline how we execute this project (see **Figure 2,** Project Flow in Appendix A).

1. Define the parameters

2. Request a sample set of data to use for implementation in Python to gain experience. This is the training set of the data
3. Request the full dataset from Company X and do supply chain mapping
4. Construct a large-scale implementation and test the full dataset
5. Create a sensitivity analysis to review the trade-offs of costs vs. CO_2 emissions

In conclusion, the model in Python will help Company X optimize their distribution network for Product A. The model will offer scenarios that show how adjusting one or more variables in their network design will affect the entire supply chain of Product A. Company X can use this model to make strategic decisions on how to adjust their current network design to support the growing business of Product A.

Chapter 2: State of the Art

For our literature review, we research the following areas: (1) challenges with perishable food supply chains, (2) environmental impact and waste, and (3) common methodologies used for network design. Lastly, we identify the type of model that is used for this capstone project.

2.1 Challenges with Perishable Food Supply Chains

The food industry is a highly competitive market that forces companies to sell products that meet demand requirements of price, quality, and quantity (Turi et al., 2014). Food quality, including safety, has been a major concern faced by the food industry, partly due to a series of food safety crises and scandals (Aung et al., 2014). Companies need to continuously evaluate what elements of their supply chain can be adjusted to meet business needs and also serve their customers the highest quality product while also remaining profitable.

Companies also face additional challenges when they ship food products that need to be refrigerated while in transit. Food product quality may decay over the span of the supply chain that is influenced by the environmental conditions (van der Vorst et al., 2009). It is typically more expensive to ship products in refrigerated vans, which are also called reefers. In October of 2022, the average national dry van rate was $2.42 per mile, whereas the rate for reefers was $2.79 (DAT Trendlines, 2022).

Food quality is extremely important to Company X and something they are not willing to sacrifice. Since Product A needs to be shipped by refrigerated vans, Company X has to pay a premium to use reefers instead of dry vans.

2.2 Environmental Impact and Waste

According to the High-Level Expert Forum - How to Feed the World in 2050 (2009), “the world’s population is predicted to reach 9.1 billion by 2050 and this will require an increase of 70% in food availability.” Since there is an increased demand for food, this also means there is potential for more food waste. It is estimated that 30% of food for human consumption is wasted or lost at some point in the supply chain (High Level Expert Forum, 2009). There is potential for operational waste of food products in production, storage, handling, and transportation (Murthy et al., 2009). Companies have to look at all stages of their supply chain in order to eliminate waste.

Sustainability is a topic that is gaining interest for researchers and professionals in the supply chain field. Supply chains that take sustainability and environmental impact into consideration are called green supply chains. Professionals and academia are interested in green supply chains due to climate change, diminishing raw material resources, overflowing waste sites, and increasing levels of pollution (Kumar et al., 2012). It is important that companies consider waste in the life cycle of their products to optimize the supply chain and to understand the total cost of a product (Kumar et al., 2012). The design of the supply chain network involves a trade-off between total fixed costs and total logistics costs, while also minimizing environmental impact.

In our model, we use an emissions factor to quantify the environmental impact of Company X’s distribution of Product A. We analyze how using less-than-truckload vs. full truckload distribution impacts Company X’s CO_2 emissions.

2.3 Common Methodologies for Network Design

Supply chain network design considers the location of production, commercialization, and distribution facilities. The supply chain network design problem comprises both strategic (e.g., determining the optimal number and geographic dispersion of the facilities) and tactical decisions (e.g., amounts of purchase, production, inventory and the intensity and frequency of the flows between these facilities) (Ramezani et al., 2014). Mathematical and computer modeling techniques have been developed by scholars to determine the expected economic outcomes of supply network designs.

Supply chain network design uses various tools and techniques to formulate a model. In our research, we discovered two main operations research methods commonly used in designing supply chain networks: simulation models and mixed integer programming models (**Table 1**).

Table 1

Tools and Reference Applied in Supply Chain Network Design

Tools	References
Simulation models	Dong (2001), Lee et al. (2002), Terzi et al. (2004) and Huan et al. (2004)
Mixed integer programming models	Kitaw et al, (2011), Paksoy et al. (2010) and Ahumada et al. (2011)

Traditional supply chain network models often assume that products do not have a shelf life. With the growing need for food, there is a significant increase in research on modeling and optimization of the food supply chain system. These models consider that perishable goods have a limited shelf life and cannot be stored in warehouses for an unlimited amount of time.

Yakavenka et al. (2019) researched a multi-objective perishable food network design and incorporates sustainability in the model. Similar to our project's design questions, this research attempts to take delivery time, cost, and environmental optimization functions as objectives. This model also integrates the decisions in the following areas, "(i) transport means, (ii) entry points selection, (iii) the locations of the operating distribution centers, and (iv) determination of the associated flows between the nodes of the supply chain." (Yakavenka et al, 2019, p.595)

Musavi et al., (2017) presented a sustainable location multi-objective model which considers the perishability in the distribution and total CO_2 emissions in the network design. Similar to our project's design questions, this research incorporated trade-offs between the total transportation cost of less-than-truckload and full truckload freight, the quality and freshness of the products at the delivery moment, the concept of scheduling for outbound vehicles, and the carbon emissions of the outbound vehicles (Musavi et al., 2017).

We did not use Yakavenka and Musavi's exact formulation, but our model uses a similar concept that evaluates the trade-offs of cost, service level, mode of transportation, and impact of CO_2 emissions.

2.4 Model Selection

In our research project, the tool we used is Mixed Integer Linear Programming. This type of model is the best tool for our project because we have multiple input variables that affect the overall cost of Company X's network design. The Mixed Integer Linear Programming model will highlight the trade-offs of our input variables we discuss in our Methodology section listed below.

Chapter 3: Methodology

In this chapter, we review the scope of what is included in the model. Next, the base model is defined and considers additional scenarios to account for different modes of transportation and for new supplier locations. Lastly, the model formulation is provided and defines the variables for each equation.

3.1 System Specification

We focus exclusively on optimizing Company X's inbound shipments from their food suppliers to their DCs in our model. We did not include outbound shipments, which is the product flow from Company X's DCs to their retail stores.

Company X has 34 distribution centers they use for operations but they also supply Product A to 15 grocer DCs. A grocer has ownership of their distribution centers. Once Company X ships to the grocer DC, they lose visibility to Product A to the grocer's individual retail stores. We included shipments from Company X food suppliers to the 15 grocer DCs in our model. Only one food supplier can ship to all grocer DCs. Currently, the West Coast supplier ships Product A to all 15 grocer DCs. (Sponsor company, personal communication, November 9, 2022)

In our model, we use the two current food suppliers in addition to nine potential new supplier locations. Depending on the scenario being tested, it is possible the product can ship from any of the 11 supplier locations. A constraint can be set in the model to only allow a specified number of suppliers to ship products to the DCs.

We collected data from Company X to define the capacity constraints for our optimization model. The capacity of units produced per week for the 11 suppliers is listed below in **Table 2**.

Table 2

Suppliers Capacity in Units Per Week

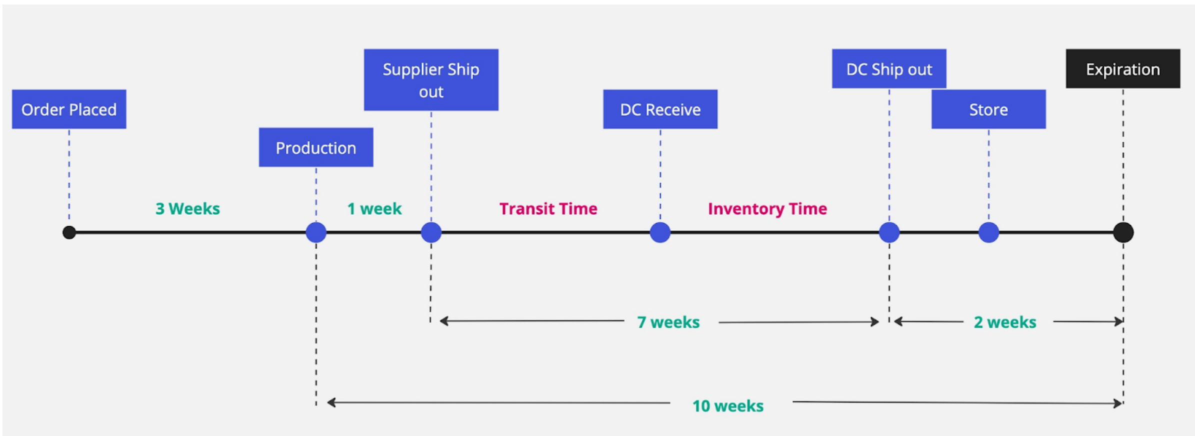
Supplier	Capacity (Units Per Week)
0	40,000
1	84,000
2	180,000
3	180,000
4	106,000
5	72,000
6	28,000
7	28,000
8	28,000
9	50,000
10	80,000

We assume that all DC locations have unlimited storage capacity. Company X has provided past shipment history from the two food suppliers to DC locations, which we use as demand for all the DCs.

Figure 3 defines the lead time assumptions our model uses to account for the expiration of the product. Our model assumes 3 weeks from when Company X places an order to the supplier to when production begins. This lead time does not consume shelf life since the product is not Work In Progress (WIP) inventory yet. Next, we assume 1 week for the supplier to produce the product and ship out to the DCs. There is a maximum 7-week lead time from when the supplier ships out product to the DCs to when the DC ships to the retail stores. The 7-week period includes transit time as well as inventory time where product is potentially waiting at the DC. A key constraint is that the product needs to have at least two weeks' shelf life before it can ship to a retail store.

Figure 3

Lead Time Assumptions for Expiration of Product A



Note. Product A has a total shelf life of 10 weeks (70 days). The shelf life is consumed by the following 3 steps: 1 week from production to supplier ship out, 7 weeks from supplier ship out to DC ship out, and 2 weeks from DC ship out to expiration.

3.2 Model Scenarios

Our research methodology is to use Mixed Integer Linear Programs in Python to identify the trade-offs of costs, service level, and CO_2 emissions. We followed the 6 steps listed below to build our model:

1. Estimate transportation cost and lead time for each route from supplier to DC for LTL and FTL
2. Calculate the optimal inventory policy for each route from supplier to DC for LTL and FTL at each defined service level (97%, 97.5%, 98%, 98.5%, 99%, 99.5%)
3. Estimate the expected number of expired units for each inventory policy developed in Step 2
4. Estimate the transportation emissions impact for each route for FTL and LTL
5. Calculate the cost minimization model with service levels considering inventory costs and transportation costs
6. Incorporate the emissions + cost-minimizing solutions for defined service levels (97%, 97.5%, 98%, 98.5%, 99%, 99.5%) to show trade-offs between these variables

3.3 Model Formulation

In the model formulation section, we defined four main sections: (1) inventory policy, (2) expiration, (3) emissions, and (4) optimization formulation.

3.3.1 Inventory Policy Formulation

The inventory policy our sponsor company uses is a Periodic Review (R,S), which is shown in **Figure 4**. This is also known as the "Order-Up-To policy" and is a two-bin system. The policy is, "Order up to S units every R time period."

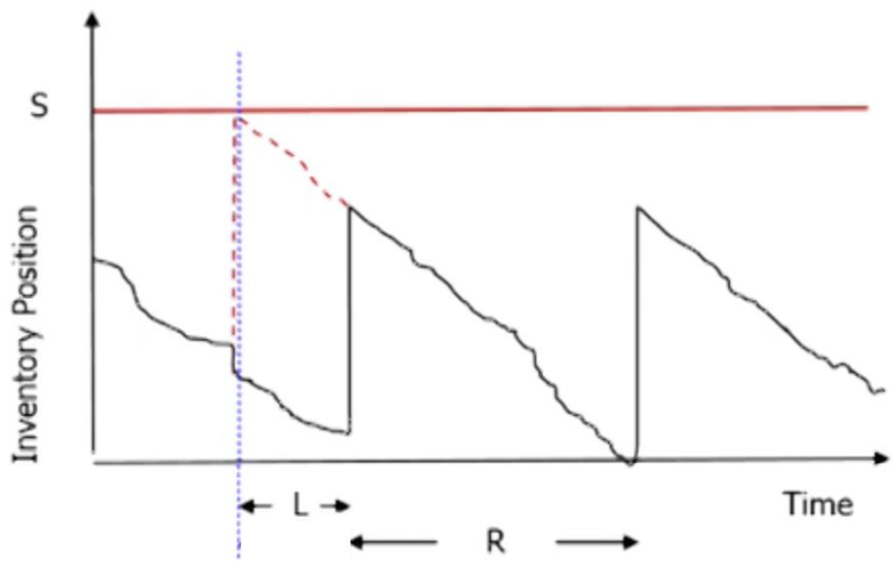
Equation (1) is the order up to point, S which equals [the sum of the expected demand over the lead time and the replenishment time] plus the [RMSE of the forecast error over lead time plus replenishment time multiplied by a safety factor, k].

$$\text{Order Up To Point, S} = \text{Cycle stock} + \text{Safety stock} \tag{1}$$

$$\mathrm{S} = \mu_{DL+R} + k\sigma_{DL+R}$$

Figure 4

Periodic Review (R,S) Graph



Resource: CTL.SC1x: Supply Chain and Logistics Fundamentals

Note. This graph represents the periodic review inventory policy which states to order up to S units every R time period.

The lead time, L, and the review period, R, both influence the total costs. Note that the inventory costs for a (R,S) system are calculated below in Equation (2):

$$\text{Inventory costs} = w_{ij} \times \text{Unit Expiration cost} + \text{Inventory holding cost} \times \left(\frac{\text{Cycle stock}}{2} + \text{Safety stock}\right) \quad (2)$$

Equation (2) implies two key relationships:

1. Increasing Lead Time, L, will increase Safety Stock non-linearly and Pipeline Inventory linearly

2. Increasing the Review Period, R, will increase the Safety Stock non-linearly and the Cycle Stock linearly

Each supplier is associated with an additional variable cost for the time period, fi for the amount of xij. The inventory cost for the inventory policy between two nodes is given by the Iij.

3.3.2 Expiration Formulation

Items will expire after 10 weeks we estimate the number of expired units for each location. Each DC has a different inventory policy depending on which supplier ships the product to the DC. If items are not shipped out of the DC 8 weeks after they are produced, they will expire (**Figure 3**). We estimate the fraction of items that will expire given the maximum inventory position and expiration time for each DC.

In Section 3.3.1, we discuss the periodic review policy to order the maximum inventory position of S. **Figure 3** shows the shelf-life consumption timeline, which states after products are ordered they are produced 3 weeks later. Products should ship to stores 11 weeks after ordering or they will expire (4 weeks from ordering to production plus 7 weeks for transit and inventory time).

The demand of this period will be:

$$\mu_{DL} = D_j \times (Time\ between\ order\ to\ produce\ plus\ expired\ time) \tag{3}$$

The standard deviation of this period will be:

$$\sigma_{DL} = \sigma_j \times (Time\ between\ order\ to\ produce\ plus\ expired\ time)^2 \quad (4)$$

The expiration variables are shown in **Table 3.**

Table 3

Expiration Variables

D_j	Demand in node *j*
σ_j	Standard deviation in node *j*
w_{ij}	Expected expiration item between two nodes *i* and *j*
S	Order to point
k	Difference, in standard deviations, between the expected demand during shelf life and maximum inventory position

The probability that an item will expire follows a normal distribution. Equation (5) and (6) describe the probability that an item expires equals the probability that the standard distribution is greater than k:

$$\text{P (expire)} = \text{P } (\text{N}(0,1)) > \text{k} \quad (5)$$

$$\text{Where k } = \left(\frac{S - \mu_{DL}}{\sigma_{DL}}\right) \quad (6)$$

Formula (7) is the expected number of items to expire, which is the standard deviation times G:

$$G(k) = NORMDIST(\text{k,0,1,0}) - k \times (1 - NORMDIST\ (k)) \quad (7)$$

Formula (8) is the actual units that expire:

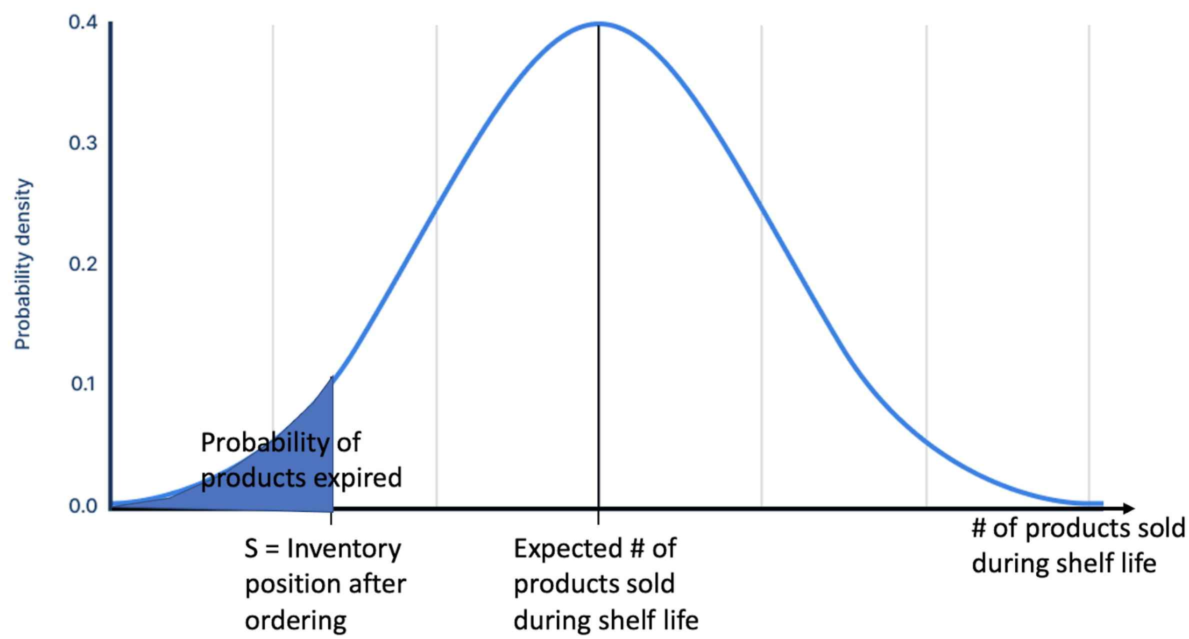
$$w = \int_{x=S}^{\infty} (x - S) \, f_x(x) dx = \sigma_{DL} \, G(\frac{S - \mu_{DL}}{\sigma_{DL}}) = \sigma_{DL} \, G(k) \tag{8}$$

To find the actual units that expire, we simply multiply G(k) times the standard deviation of the probability distribution.

The expected expired fraction of items is the number of items divided by average order quantity (demand*R). **Figure 5** shows the probability of products expired in the shaded blue section to the left of the normal distribution curve.

Figure 5

Distribution Graph for the Probability of Products Expired

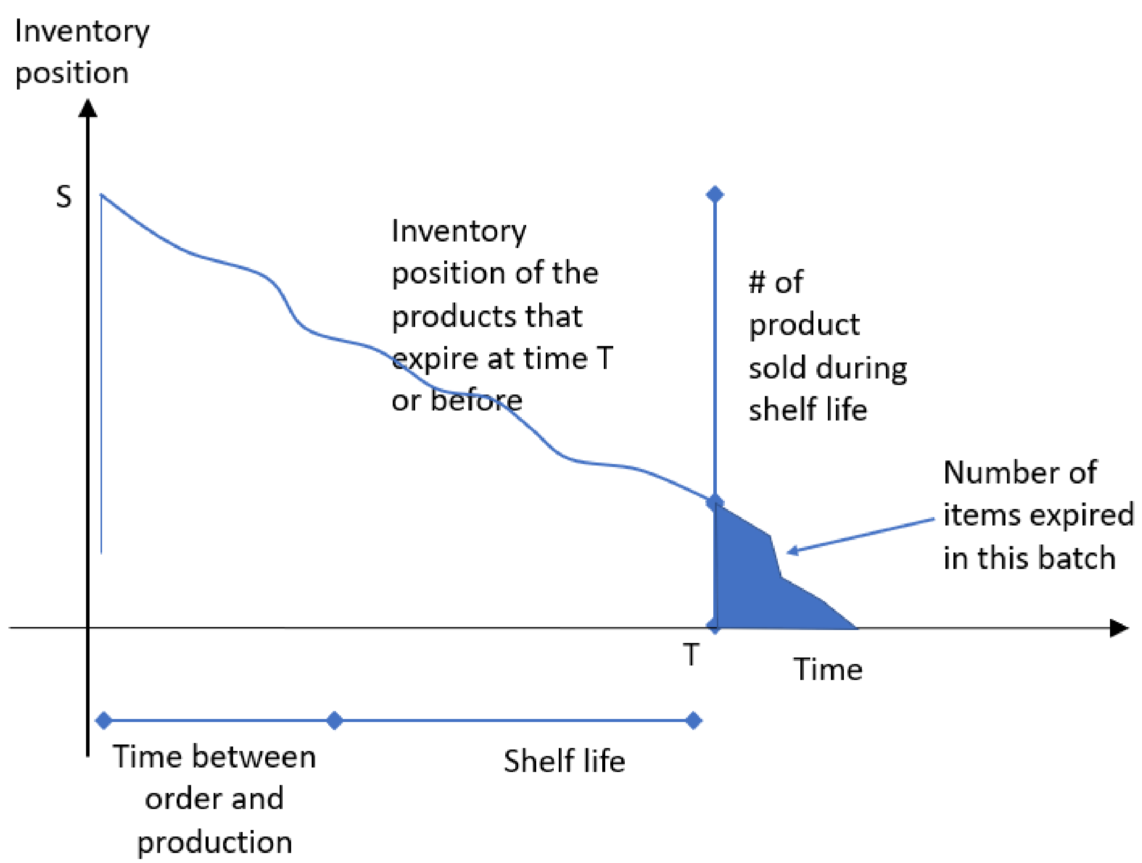


Note. **Figure 5** shows the probability of products expired in the shaded blue section to the left of the normal distribution curve.

Figure 6 is a similar graph to the previous figure, however this visual shows one order cycle and the number of items expired. The Y axis is the inventory position and the X axis is the shelf life. The shaded section in blue on the right side of the graph represents leftover inventory that was not consumed within 8 weeks, so this product cannot be shipped to retail stores from the DC.

Figure 6

Graph of Number of Items Expired in Order Cycle



Note. The shaded section in blue represents the number of items expired in one order batch. The shelf life is on the X axis and represents the 10-week shelf life. Inventory that is not consumed after the shelf life is considered expired inventory.

3.3.3 Emissions Formulation

In order to quantify CO_2 impact for our models, we used two different methodologies to calculate emissions for less than truckload shipments and full truckload shipments. For LTL shipments, we used an activity-based estimation called The Greenhouse Gas (GHG) Protocol methodology, Equation (9). This method takes into account the weight, distance traveled, and an emissions factor of 0.211 CO_2/kg:

The Greenhouse Gas (GHG) Protocol methodology

$$\mathrm{TE} = \mathrm{EF} * \mathrm{W} * d_{ij} \tag{9}$$

TE: Total emissions

EF: Emission factor (0.211 CO_2/kg)

W: Weight of cargo

d_{ij}: Distance traveled between i and j

For full truckload shipments, we used a fuel-based approach called, The Network for Transport Measures (NTM) methodology, which is shown in Equation (10):

The Network for Transport Measures (NTM) methodology

$$TE = CE \times d_{ij} \times \left(f_e \cdot \left\lceil \frac{D_j}{C} \right\rceil + (f_f - f_e) \right) \times \frac{D_j}{C} \tag{10}$$

TE: Total emissions

CE: 2.6 Kg of CO_2/liter of diesel

d_{ij}: Distance traveled between i and j

f_f: Fuel consumption factor when the vehicle is full (0.294 L/km)

f_e: Fuel consumption factor when the vehicle is empty (0.201 L/km)

C =Truck capacity

3.3.4 Optimization Formulation

The network is formed by a set of supply nodes *V*, and a set of demand nodes *D*. There are transportation arcs *ij* from supply nodes $i \in V$ to demand nodes $j \in D$.

We used the parameter variables listed in **Table 4** and the decision variables listed in **Table 5** for of our mathematical model:

Table 4

Parameter Variable Description

Variable	Description
V_i	Supply capacity in node *i*
D_j	Demand in node *j*
c_{ij}	Transportation cost in arc *ij*
L_{ij}	Each arc is associated with a transportation lead time
e_{ij}	Each arc is associated with an emission measurement
x_{ij}	The amount of units transported on each arc *ij* is denoted
d_{ij}	The distance of units transported on each arc *ij* is denoted
M	An arbitrary large number, specific to each arc (but the value could be the same between arcs)

Table 5

Decision Variable Description

Variable	Description
x_{ij}	The amount of units transported on each arc *ij* is denoted
$Y_i = 1$	The integer value to describe whether supplier (*i*) is used
$Y_i = 0$	The integer value to describe whether supplier (*i*) is not used
t_{ij}	The number of trucks used on each arc *ij* is denoted
r_{ij}	Represents whether the route from supplier (*i*) to DC (*j*) is used or not

Equation (11) and (12) are the objective functions and are formulated below:

$$Minimize \quad Cost = \sum_i \sum_j c_{ij} * x_{ij} + \sum_i \sum_j c_{ij} * t_{ij} + \sum_i \sum_j I_{ij} * r_{ij} + \sum_i \sum_j f_i * x_{ij} \tag{11}$$

$$Emission = \sum_i \sum_j e_{ij} * r_{ij} \tag{12}$$

Equation (13) is the supply constraint – the total number of shipped units from a supply node i to all demand nodes j must be less than (or equal to) the supply capacity of node i.

$$\sum_j x_{ij} \leq V_i \quad \forall i \in \mathrm{V} \tag{13}$$

Equation (14) is the demand constraint – the number of shipped units to a demand node j from all supply nodes i must be at least the demand at node j.

$$\sum_i x_{ij} \geq D_j \quad \forall j \in \mathrm{D} \tag{14}$$

Equation (15) and Equation (16) are the non-negativity constraints (for x's) and the binary constraints (for the Y's):

$$x_{ij} \geq 0 \quad \forall ij \tag{15}$$

$$Y_i = \{0,1\} \quad \forall i \tag{16}$$

Equation (17) is the constraints on the maximum number of facilities to use – the sum of the Y-variables will be the total number of facilities in use.

$$\sum_i Y_i \leq P_{max} \tag{17}$$

P_{max}: Maximum number of facilities

Equation (18) is the linking constraint to ensure that we do not allocate shipments to a location that is not used. The units shipped on an arc must be less than (or equal to) a large number times the r associated with the node where the transport routes:

$$x_{ij} - M r_{ij} \leq 0 \quad \forall ij \tag{18}$$

Equation (19) is the constraint accounting for target lead time:

$$r_{ij} L_{ij} \leq \text{target lead time} \tag{19}$$

Equation (20) is the constraint accounting if the quantity of units shipped from two nodes are more than truck capacity, the additional truck would be added.

$$t_{ij} > x_{ij} / \text{truck capacity} \qquad t_{ij} \in \mathrm{I} \quad \forall ij \tag{20}$$

Chapter 4: Results and Analysis

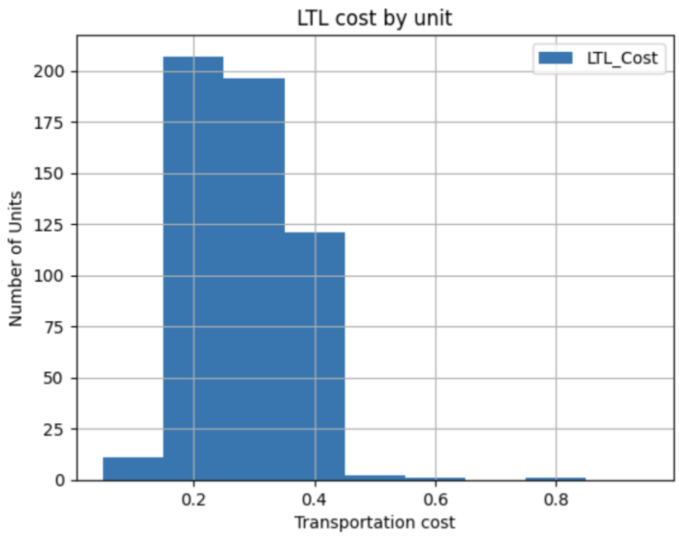
In this chapter, we review initial findings based on historical data for cost per unit/shipment and transit times for all shipments with LTL vs. FTL transportation. Next, we present a matrix that creates various scenarios for how many suppliers to open and analyzed the cost benefit of adding more suppliers to the network. We also analyze the impact of adding cost of goods sold to the model and compare the impact to overall cost. Lastly, we provide graphs that show the trade-offs with service level and costs for number of expired items and CO_2 emissions.

4.1 Initial Findings

First, we explore the historical shipment data from the food suppliers to the DCs. **Figure 7** shows the cost per unit for less than truckload shipments. All LTL shipments are less than $1 per unit. **Figure 8** shows FTL shipments, which are measured by a shipment level since the number of units per truck can vary. FTL costs by shipment range from $500 to $8,300. If looking at FTL shipments at a unit level, the unit cost of FTL shipment ranges from $1 to $24. Based on historical data, most of the shipments are sent by full truckload. There is an opportunity for our sponsor company to utilize LTL shipments to gain economies of scale.

Figure 7

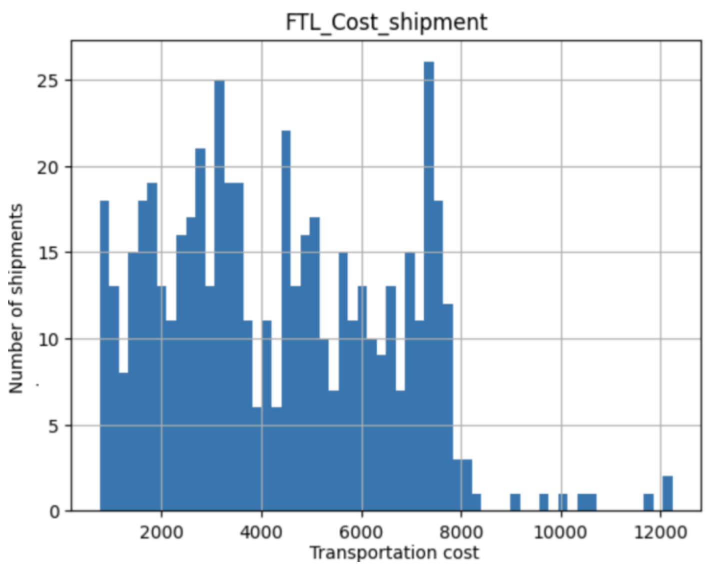
LTL Cost Per Unit Graphs



Note. **Figure 7** shows the cost per unit for all LTL shipments.

Figure 8

Graph of FTL Cost Per Shipment



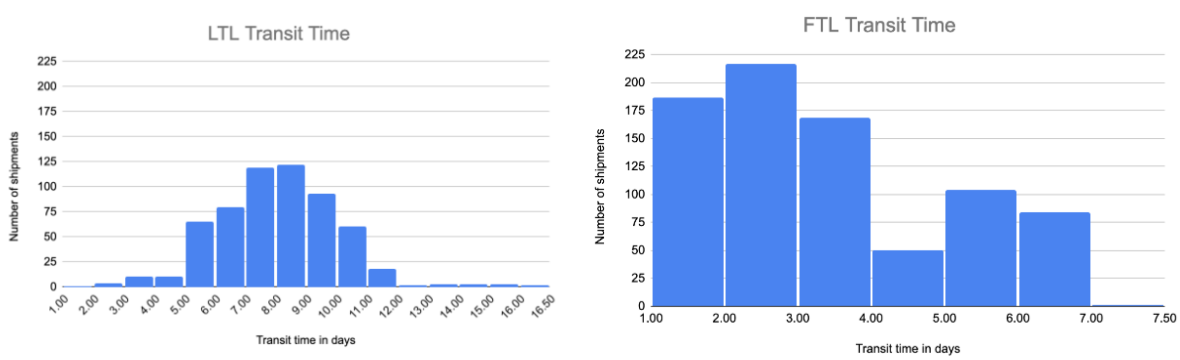
Note. **Figure 8** shows the cost per shipment for all FTL shipments.

Company X ships more frequently with FTL, which is more expensive per unit compared to LTL. If we converted the shipment cost of FTL into unit cost, 6% of FTL shipments cost more than $10 per unit.

Next, we analyzed the transit time of historical shipments for LTL vs. FTL, as shown in **Figure 9**. The average transit time for LTL is 7.5 days whereas the maximum FTL transit time is 7 days. LTL shipments range from 1 day to 16 days. The LTL transit time has a normal distribution shape compared to FTL transit time, where the majority of shipments are 1 to 3 days.

Figure 9

Transit Times (LTL vs. FTL) Graphs



Note. The 2 graphs in **Figure 9** show the transit time for all shipments for LTL vs. FTL. Our sponsor company ships more frequently with FTL.

4.2 Scenario 1: Matrix with 11 Scenarios with Number of Suppliers Open: Transportation Cost

Scenario 1 is our base model, which is shown in **Table 6**. This table defines the recommended network design based only on the transportation cost for each route (Supplier to DC) and each transportation mode (FTL and LTL). **Table 6** shows 11 scenarios to represent which suppliers the model suggests using, depending on how many suppliers Company X wants to use to supply Product A. For example, if our sponsor company wants to use 3 suppliers, our model recommends using Supplier 0, 1, and 6.

Table 6

Recommended Supplier Locations Based on Number of Suppliers in Operation

Supplier	1 suppliers	2 suppliers	3 suppliers	4 suppliers	5 suppliers	6 suppliers	7 suppliers	8 suppliers	9 suppliers	10 suppliers	11 suppliers
0	0.0	39709.0	38289.0	36467.0	36467.0	33667.0	31712.0	31712.0	31712.0	31712.0	31712.0
1	0.0	78355.0	61942.0	54640.0	40166.0	36901.0	36901.0	36901.0	30655.0	30655.0	30655.0
2	118064.0	0.0	0.0	0.0	0.0	0.0	0.0	5806.0	5806.0	5806.0	5806.0
3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1124.0	1124.0
5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	7520.0	7520.0	7520.0
6	0.0	0.0	17833.0	13041.0	13041.0	13041.0	9061.0	9061.0	9061.0	7937.0	7937.0
7	0.0	0.0	0.0	0.0	0.0	0.0	8385.0	8385.0	8385.0	8385.0	8385.0
8	0.0	0.0	0.0	13916.0	13916.0	9752.0	7302.0	7302.0	7302.0	7302.0	7302.0
9	0.0	0.0	0.0	0.0	14474.0	13200.0	13200.0	7394.0	7394.0	7394.0	7394.0
10	0.0	0.0	0.0	0.0	0.0	11503.0	11503.0	11503.0	10229.0	10229.0	10229.0

Table 7 displays the total transportation cost if three suppliers are in operation and how many units are suggested to ship per week by FTL or LTL transportation. The total transportation cost for three suppliers is $21,219. It is important to note that only LTL shipments are recommended by the model.

Table 7

Total Transportation Cost for Three Suppliers in Operation

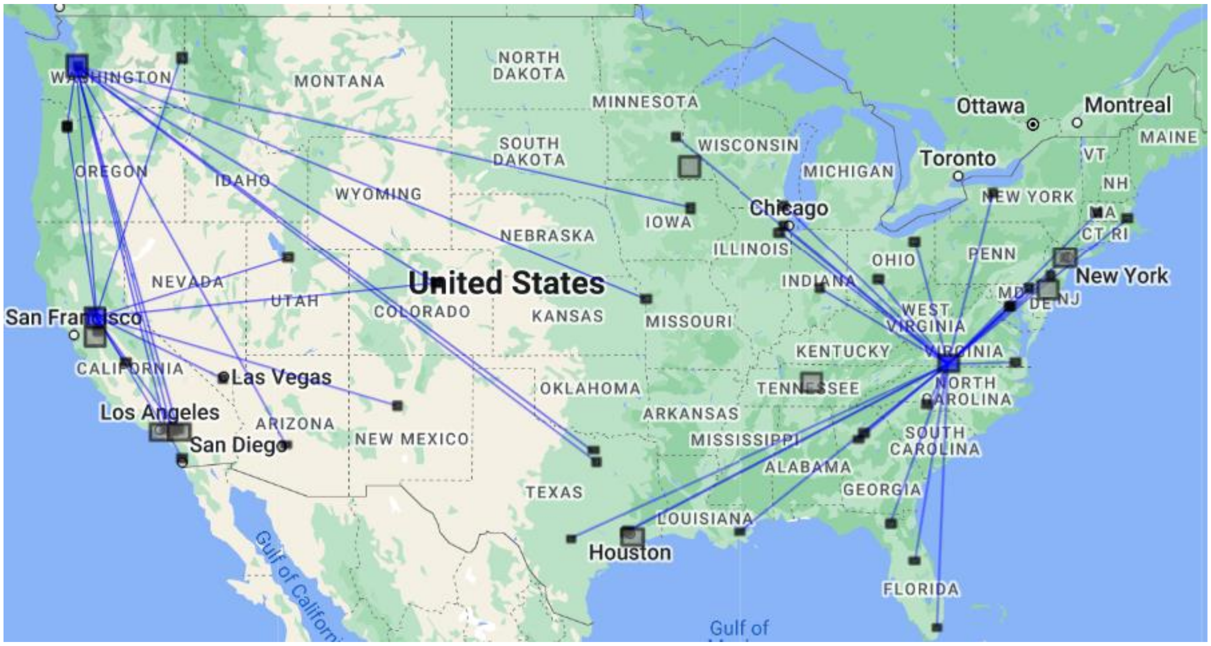
Total Transportation Cost: $ 21219.171372031775

Supplier	Open?	FTL Flow	FTL Truck Flow	LTL Flow
0	1	0.0	0.0	38289.0
1	1	0.0	0.0	61942.0
2	0	0.0	0.0	0.0
3	0	0.0	0.0	0.0
4	0	0.0	0.0	0.0
5	0	0.0	0.0	0.0
6	1	0.0	0.0	17833.0
7	0	0.0	0.0	0.0
8	0	0.0	0.0	0.0
9	0	0.0	0.0	0.0
10	0	0.0	0.0	0.0

Our model has a feature built with Google Maps that visually displays which suppliers ship to each DC. **Figure 10** shows the scenario if a constraint is set to a maximum of 3 suppliers. The blue lines indicate LTL transportation.

Figure 10

Visual Representation of Shipment Routes for 3 Suppliers



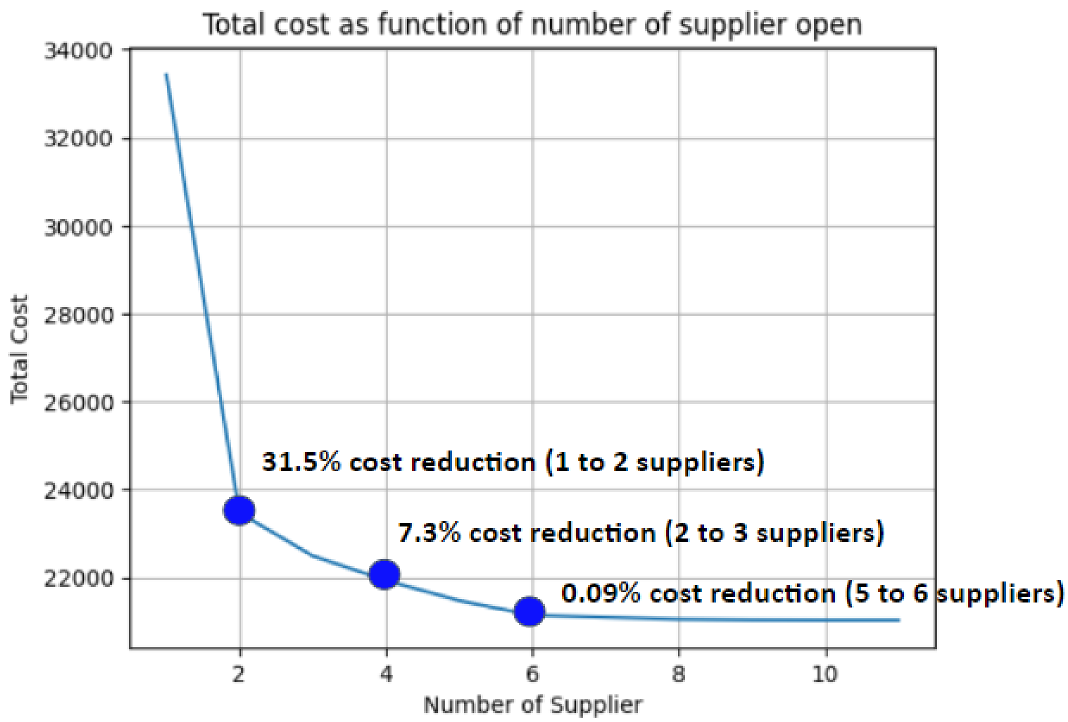
Note. This map shows the selected routes with constraint set to a maximum of 3 suppliers.

Lastly, we explore the impact to transportation cost if additional suppliers are added to the distribution network. **Figure 11** shows 3 key relationships shown below:

1. 31.5% cost reduction with 1 to 2 suppliers
2. 7.3% cost reduction with 2 to 3 suppliers
3. 0.009% cost reduction with 5 to 6 suppliers

Figure 11

Chart of Costs for Opening Additional Suppliers



Note. **Figure 11** shows the impact to transportation cost if additional suppliers are added to the distribution network. A key takeaway is that there is not a cost benefit for Company X to use more than 3 suppliers in the distribution network based on current demand volumes.

4.3 Scenario 1.1: Matrix with 11 Scenarios with Number of Suppliers Open Excluding Supplier 0 - Transportation Cost

Our sponsor company is considering an exit from Supplier 0. **Table 8** shows 11 scenarios to represent what suppliers the model suggests using depending on how many suppliers Company X wants in operation excluding Supplier 0. If there are three suppliers in operation, the model now recommends using Supplier 1, 4, and 8 which is different from the output of Scenario 1.

Table 8

Recommended Supplier Locations Excluding Supplier 0

Supplier	1 suppliers	2 suppliers	3 suppliers	4 suppliers	5 suppliers	6 suppliers	7 suppliers	8 suppliers	9 suppliers	10 suppliers	11 suppliers
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	0.0	73166.0	57440.0	57440.0	50101.0	36901.0	36901.0	30655.0	30655.0	30655.0	30655.0
2	118064.0	0.0	0.0	0.0	0.0	0.0	5806.0	5806.0	5806.0	5806.0	5806.0
3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2322.0	2322.0
4	0.0	44898.0	39163.0	0.0	0.0	0.0	0.0	0.0	7292.0	7292.0	7292.0
5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	7520.0	7520.0	7520.0	7520.0
6	0.0	0.0	0.0	21952.0	21952.0	21952.0	21952.0	21952.0	14660.0	14660.0	14660.0
7	0.0	0.0	0.0	22946.0	19661.0	19661.0	19661.0	19661.0	19661.0	17339.0	17339.0
8	0.0	0.0	21461.0	15726.0	13904.0	13904.0	13904.0	13904.0	13904.0	13904.0	13904.0
9	0.0	0.0	0.0	0.0	0.0	13200.0	7394.0	7394.0	7394.0	7394.0	7394.0
10	0.0	0.0	0.0	0.0	12446.0	12446.0	12446.0	11172.0	11172.0	11172.0	11172.0

4.4 Scenario 2: Matrix with 11 Scenarios with Number of Suppliers - Transportation Cost and COGS

In this scenario, we are considering costs of goods sold (COGS) in addition to transportation costs in our model. **Table 9** defines the recommended network design based on the transportation cost and COGS for each route (Supplier to DC) and each transportation mode (FTL and LTL). **Table 9** shows 11 scenarios to represent which suppliers the model suggests using depending on how many suppliers our sponsor company wants in operation. A key finding is the model recommends opening only two suppliers, Supplier 2 and 3, regardless of the constraint for a maximum number of suppliers. **Figure 12** shows how there is no cost benefit to open more than 2 suppliers because all the demand can be fulfilled with Suppliers 2 and 3.

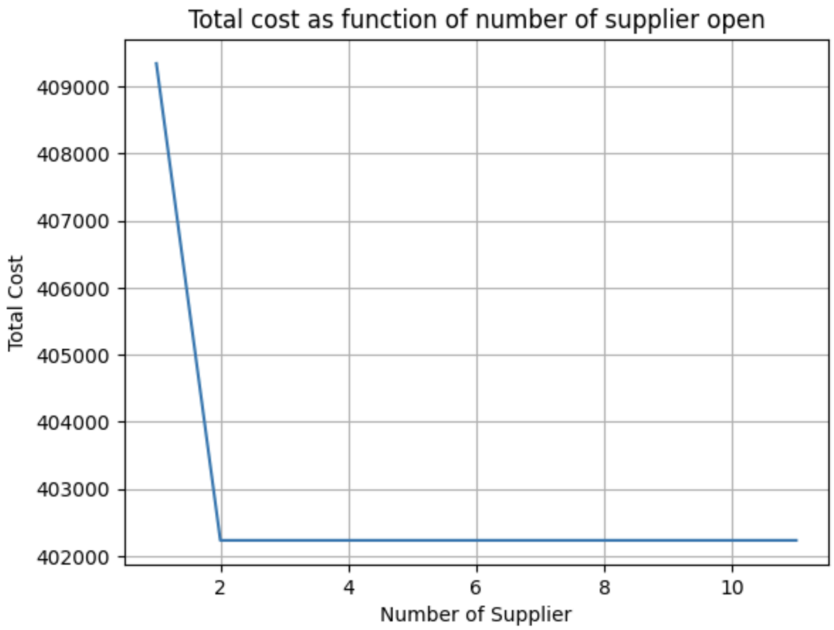
Table 9

Recommended Supplier Locations with COGS

Supplier	1 suppliers	2 suppliers	3 suppliers	4 suppliers	5 suppliers	6 suppliers	7 suppliers	8 suppliers	9 suppliers	10 suppliers	11 suppliers
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	118064.0	66018.0	66018.0	66018.0	66018.0	66018.0	66018.0	66018.0	66018.0	66018.0	66018.0
3	0.0	52046.0	52046.0	52046.0	52046.0	52046.0	52046.0	52046.0	52046.0	52046.0	52046.0
4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Figure 12

Chart of Costs for Opening Additional Suppliers with COGS



Note: **Figure 12** shows the impact on transportation costs and COGS if additional suppliers are added to the distribution network. Compared to transportation costs, the cost of COGS is much higher. Therefore, COGS weighs heavily on the total cost. The model always suggests picking the supplier with the cheapest COGS and using the transportation method with the lowest cost to serve all the demand. Since the two selected suppliers can serve all the demand, the model would not suggest adding additional suppliers beyond the two.

4.5 Scenario 3: Matrix with 11 Scenarios with Number of Suppliers - Transportation Cost and Inventory Cost

In addition to factoring in transportation expenses, we incorporated the cost of inventory into our model. **Table 10** outlines the optimal network configuration based on both transportation expenses and inventory cost for each route (Supplier to DC) and transportation mode (FTL and LTL). **Table 10** presents 11 scenarios that indicate with service level of 97%, which suppliers the model recommends depending on the number of suppliers Company X intends to utilize for providing Product A. **Table 11** shows the scenario of limiting the number of suppliers to a maximum of three and how many units should be shipped by each mode of transportation. The model was revised to account for inventory expiration time, and both full truckload (FTL) and less-than-truckload (LTL) transportation modes are recommended for this scenario. According to the revised model for the maximum of three suppliers, Suppliers 0, 1, and 4 are suggested as the optimal choices. **Figure 13** shows the impact on transportation costs and inventory cost if additional suppliers are added to the distribution network. After adding up to 6 suppliers in the distribution network based on current demand volumes, the cost benefit for Company X becomes very minor.

Table 10

Recommended Supplier Locations with Transportation and Inventory Costs

Supplier	1 suppliers	2 suppliers	3 suppliers	4 suppliers	5 suppliers	6 suppliers	7 suppliers	8 suppliers	9 suppliers	10 suppliers	11 suppliers
0	0.0	39709.0	32121.0	27499.0	27499.0	27499.0	25544.0	25544.0	25544.0	25544.0	25544.0
1	0.0	78355.0	61942.0	53601.0	36974.0	33474.0	33474.0	27228.0	27228.0	27228.0	27228.0
2	118064.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5806.0	5806.0	5806.0
3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	0.0	0.0	24001.0	21659.0	21659.0	19209.0	15229.0	15229.0	15229.0	7292.0	7292.0
5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	10947.0	10947.0	10947.0	10947.0
6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	7937.0	7937.0
7	0.0	0.0	0.0	0.0	0.0	0.0	8385.0	8385.0	8385.0	8385.0	8385.0
8	0.0	0.0	0.0	0.0	0.0	9752.0	7302.0	7302.0	7302.0	7302.0	7302.0
9	0.0	0.0	0.0	0.0	16627.0	16627.0	16627.0	13200.0	7394.0	7394.0	7394.0
10	0.0	0.0	0.0	15305.0	15305.0	11503.0	11503.0	10229.0	10229.0	10229.0	10229.0

Table 11

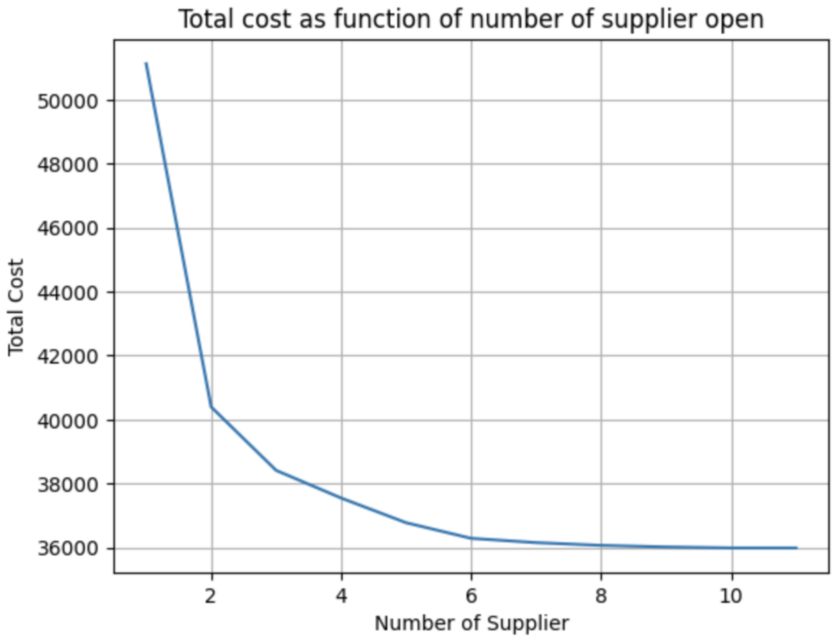
Recommended Supplier Locations and Transportation Modes with Maximum of Three Suppliers – Transportation and Inventory Costs

Total transportation and inventory cost 38409.75639759151

Supplier	Open?	FTL Flow	FTL Truck Flow	LTL Flow
0	1	0.0	0.0	32121.0
1	1	0.0	0.0	61942.0
2	0	0.0	0.0	0.0
3	0	0.0	0.0	0.0
4	1	6168.0	1.0	17833.0
5	0	0.0	0.0	0.0
6	0	0.0	0.0	0.0
7	0	0.0	0.0	0.0
8	0	0.0	0.0	0.0
9	0	0.0	0.0	0.0
10	0	0.0	0.0	0.0

Figure 13

Chart of Costs for Opening Additional Suppliers – Transportation and Inventory



4.6 Scenario 4: Matrix with 11 Scenarios with Number of Suppliers Open Excluding Supplier 0 - Transportation Cost and Inventory Cost

Table 12 shows 11 scenarios to represent what suppliers the model suggests using, depending on how many suppliers Company X wants in operation excluding Supplier 0. If there are three suppliers in operation, the model now recommends using Supplier 1, 4, and 8 which is different from the output of Scenario 1.

Table 12

Recommended Supplier Locations Excluding Supplier 0 - Transportation and Inventory

Supplier	1 suppliers	2 suppliers	3 suppliers	4 suppliers	5 suppliers	6 suppliers	7 suppliers	8 suppliers	9 suppliers	10 suppliers	11 suppliers
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	0.0	73166.0	53601.0	50101.0	33474.0	33474.0	27228.0	27228.0	27228.0	27228.0	27228.0
2	118064.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5806.0	5806.0	5806.0
3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2322.0	2322.0
4	0.0	44898.0	41613.0	39163.0	39163.0	21952.0	21952.0	7292.0	7292.0	7292.0	7292.0
5	0.0	0.0	0.0	0.0	0.0	0.0	10947.0	10947.0	10947.0	10947.0	10947.0
6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	14660.0	14660.0	14660.0	14660.0
7	0.0	0.0	0.0	0.0	0.0	19661.0	19661.0	19661.0	19661.0	17339.0	17339.0
8	0.0	0.0	0.0	16354.0	16354.0	13904.0	13904.0	13904.0	13904.0	13904.0	13904.0
9	0.0	0.0	0.0	0.0	16627.0	16627.0	13200.0	13200.0	7394.0	7394.0	7394.0
10	0.0	0.0	22850.0	12446.0	12446.0	12446.0	11172.0	11172.0	11172.0	11172.0	11172.0

4.7 Scenario 5: Matrix with 11 Scenarios with Number of Suppliers - Transportation Cost, COGS, and Inventory Cost

Table 13 outlines the optimal network configuration based on all transportation expenses, COGS, and inventory cost for each route (Supplier to DC) and transportation mode (FTL and LTL). **Table 13** shows 11 scenarios that indicate the model recommendation depending on the number of suppliers Company X intends to utilize for providing Product A with service level of 97%. **Table 14** shows the scenario of limiting the number of suppliers to a maximum of three and how many units should be shipped by each mode of transportation. The model was revised to account for inventory expiration time, and both full truckload (FTL) and less-than-truckload (LTL) transportation modes are recommended for this scenario. According to the revised model for the maximum of three suppliers, only two suppliers (Supplier 2 and 3) are recommended.

Table 13

Recommended Supplier Locations - Transportation Cost, COGS, and Inventory Cost

Supplier	1 suppliers	2 suppliers	3 suppliers	4 suppliers	5 suppliers	6 suppliers	7 suppliers	8 suppliers	9 suppliers	10 suppliers	11 suppliers
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	118064.0	66018.0	66018.0	66018.0	66018.0	66018.0	66018.0	66018.0	66018.0	66018.0	66018.0
3	0.0	52046.0	52046.0	52046.0	52046.0	52046.0	52046.0	52046.0	52046.0	52046.0	52046.0
4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 14

Recommended Supplier Locations and Transportation Modes with Maximum of Three Suppliers – Transportation Cost, COGS, and Inventory Cost

```
Total transportation, inventory and COGS: 419459.5775505594
```

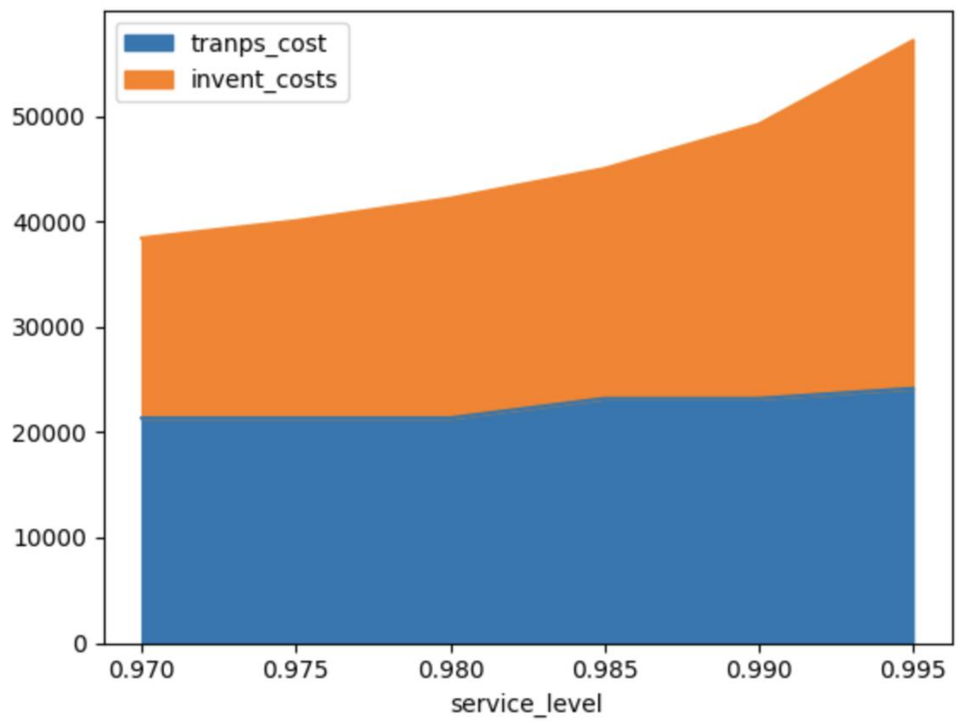
Supplier	Open?	FTL Flow	FTL Truck Flow	LTL Flow
0	0	0.0	0.0	0.0
1	0	0.0	0.0	0.0
2	1	3744.0	1.0	62274.0
3	1	0.0	0.0	52046.0
4	0	0.0	0.0	0.0
5	0	0.0	0.0	0.0
6	0	0.0	0.0	0.0
7	0	0.0	0.0	0.0
8	0	0.0	0.0	0.0
9	0	0.0	0.0	0.0
10	0	0.0	0.0	0.0

4.8 Scenario 6: Impact to Costs and Service Level with COGS

We explored the relationship of how transportation and inventory costs are impacted as service level changes. **Figure 14** shows that as service level increases from 97% to 99.5%, transportation costs remain fairly constant. However, inventory costs increase as service level increases.

Figure 14

Transportation and Inventory Costs by Service Level

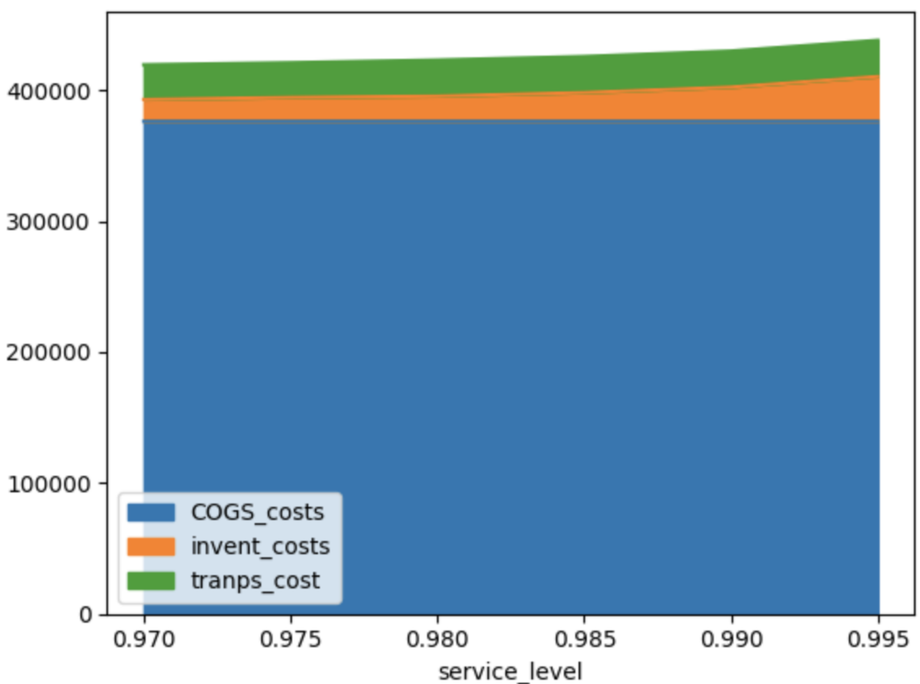


Note. **Figure 14** compares transportation and inventory costs as service level changes. Transportation costs remain constant and inventory costs gradually increase as service level increases.

Next, we analyzed how costs are impacted if we include costs of goods sold (COGS) in the total costs. **Figure 15** shows that total costs significantly increase if COGS are added into the model. COGS remain constant across all service levels and account for around $376,000. Inventory and transportation costs are minor if COGS are considered. In this scenario, inventory cost increases as service level increases and COGS and transportation costs remain relatively constant for all service levels.

Figure 15

Transportation and Inventory Costs + COGS by Service Level

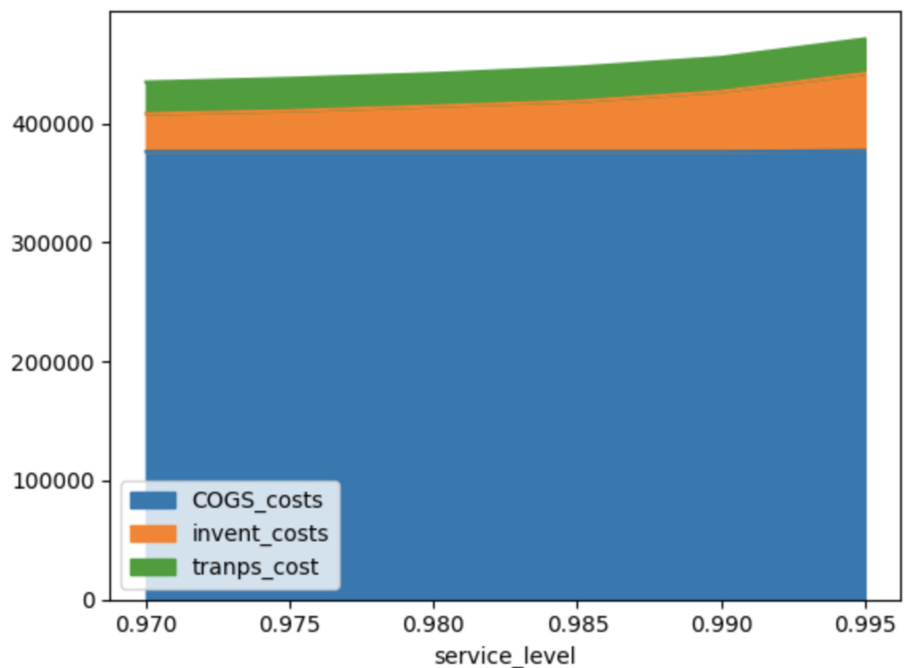


4.9 Scenario 7: Impact to Costs and Service Level with COGS with Longer Reorder Period

Our sponsor company's current reorder period for Product A is one week. We explored changing the reorder period from one week to two weeks. **Figure 16** captures how transportation, COGS, and inventory costs are impacted as the service level changes. **Figure 16** shows that when the reorder period increases by one additional week, inventory costs will increase, as Company X will be carrying more inventory every period. Transportation cost will decrease with longer reorder periods.

Figure 16

Transportation and Inventory Costs + COGS by Service Level with 2 Week Reorder Period



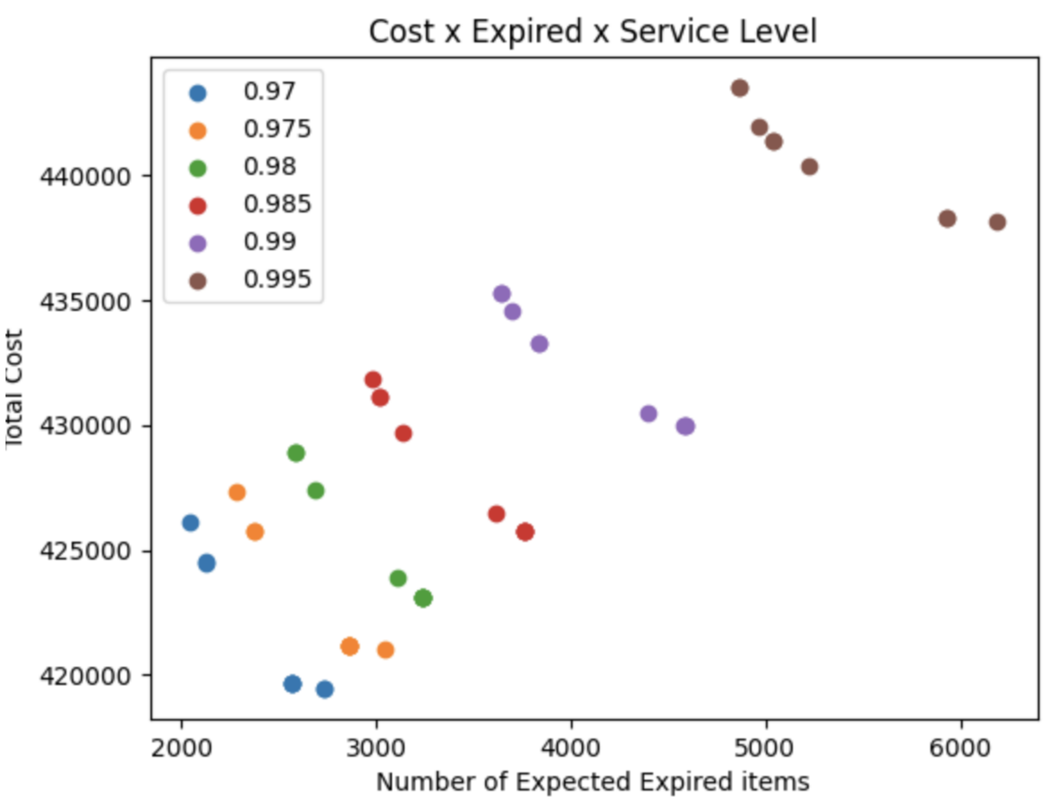
Note. **Figure 16** shows that total costs significantly increase with additional one week on recorder cycle. COGS remain constant across all service levels and account for around $376,000, but inventory cost has increased significantly as service level increases.

4.10 Scenario 8: Costs and Expired Items by Service Level

Scenario 8 evaluates the impact of costs and expired items based on service level, which is shown in **Figure 17**. This graph shows the optimal inventory policy, for each route, for each transportation mode, and for each service level. Total costs are on the Y axis and include transportation costs, inventory costs, and COGS. The number of expected expired items is on the X axis. Each colored time series represents a defined service level. For example, the orange time series represents a 97.5% service level. Each colored time series are optimal solutions and show the tradeoffs of total cost and number of expected expired items per week.

Figure 17

Total Cost and Number of Expected Expired Items Per Week by Service Level



Note. Each time series represents a defined service level referenced in the graph legend. The line graph shows the tradeoff total cost and the number of expected expired items for each service level. For each time series, as the cost decreases the number of expected expired items also increases.

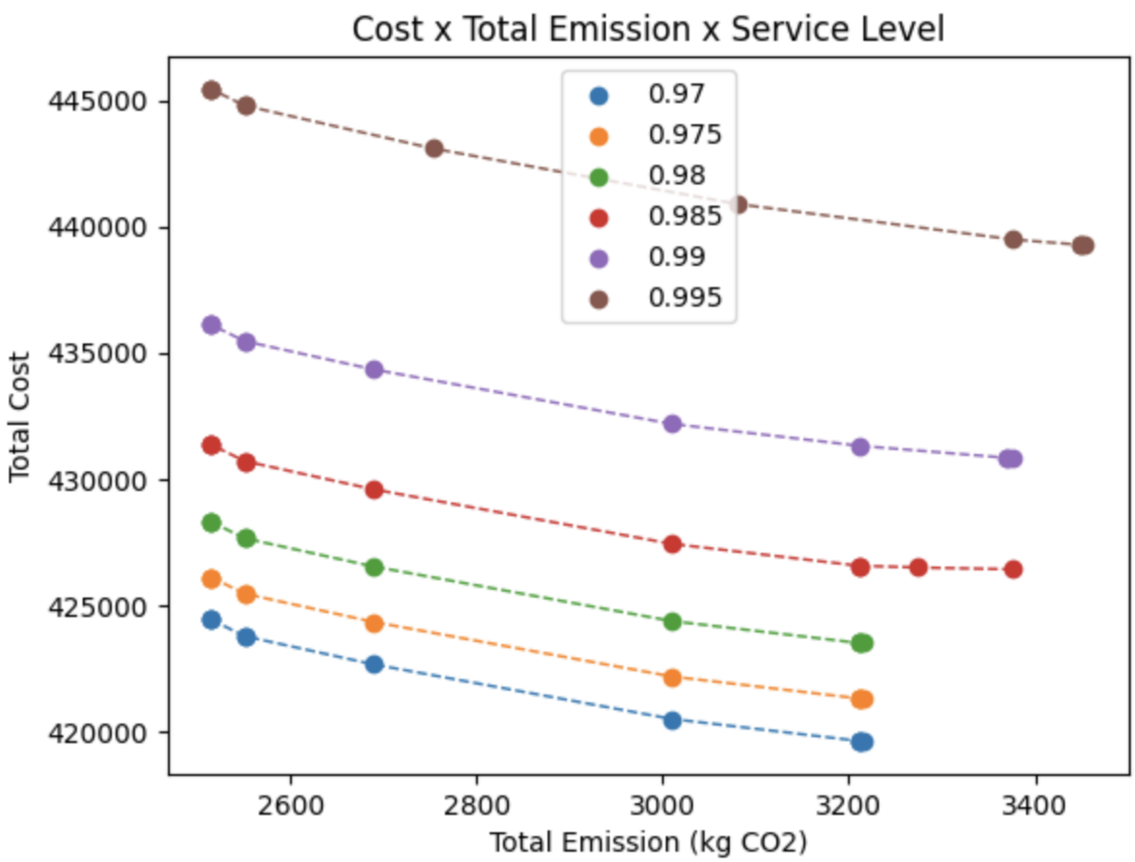
Figure 17 gives Company X the ability to choose how they prioritize service level, total costs, and number of expected expired items. The graph suggests that if the company wants to achieve a higher service level, the total costs will be higher in comparison to the total costs of a lower service level. For each time series, as the cost decreases the number of expected expired items also increases.

4.11 Scenario 9: Costs and Emissions by Service Level

Scenario 9 evaluates the impact of costs and emissions based on service level, which is shown in **Figure 18**. This graph shows the optimal inventory policy, for each route, for each transportation mode, and for each service level. Total costs are on the Y axis and include transportation costs, inventory costs, and COGS. Total emissions (kg CO_2) per week is on the X axis. Each colored time series represents a defined service level. For example, the blue time series represents a 97% service level. The blue dots are optimal solutions and show the tradeoffs of total cost and emissions (kg CO_2) per week.

Figure 18

Total Cost and Emissions Per Week by Service Level



Note. Each time series represents a defined service level referenced in the graph legend. The line graph shows the tradeoff total cost and emissions (kg CO_2) for each service level. For each time series, as the cost decreases the total emissions also increases.

It is important to note that **Figure 17** which shows the relationship between cost and expired items, have a similar shape to the graph in **Figure 18,** that shows the relationship between costs and total emissions.

Chapter 5: Discussion

In this chapter, we review key takeaways from the capstone project. We discuss the FTL vs. LTL transit times, cost of adding additional suppliers, impact of excluding Supplier 0, considering COGS in the model, trade-offs with expired items and emissions, and other areas to explore.

5.1 FTL vs. LTL Transit Times

The sponsor company hypothesized that LTL transit times are significantly longer than FTL transit times. Once we analyzed the historical data, we discovered the average LTL transit time is about one week. There is opportunity for our sponsor company to utilize LTL transportation and take advantage of the economies of scale without sacrificing more than a week of shelf-life consumption of the product.

5.2 Cost of Adding Additional Suppliers

The sponsor company operates with two suppliers. Our model shows that there is a cost benefit to adding an additional supplier when only considering transportation costs. There is a 7.3% cost reduction for transportation when a third supplier is added. The model recommends to opening Supplier 6 if the current two suppliers remain in operation.

When transportation and inventory cost are considered, there is still a reduction in total costs to add more than two suppliers to the network. There is no cost benefit from adding more than six suppliers. The sponsor company should consider adding a third or fourth supplier to the network.

5.3 Excluding Supplier 0

We reran our model and created a constraint that excluded Supplier 0. If the sponsor company wants to operate with a maximum of three suppliers, the model recommends opening Supplier 1, 4, and 8. The model selects Supplier 1, 4, and 8 if only transportation costs are considered as well as inventory plus transportation costs. The sponsor company can use these results to consider what new location they want to add to their current network design if they want to exclude Supplier 0.

5.4 Considering COGS in the Model

When costs of goods sold (COGS) are added to the model, the results significantly change. The model will automatically pick the suppliers with the cheapest COGS and opt to not add additional suppliers once all the demand is fulfilled. Since Supplier 2 and 3 have the lowest COGS, the model automatically picks these two suppliers even if there is not a constraint of adding only two suppliers.

The sponsor company should focus on the tradeoffs between inventory and transportation costs when considering which suppliers' they want to add to the network. When COGS is also considered with transportation and inventory costs, COGS make up a significant portion of total costs. Transportation and inventory costs are extremely minor compared to COGS. Another key relationship is that, as service level increases, COGS remains fairly constant. If COGS are also considered, the model will always recommend Company X to use the cheapest suppliers.

5.5 Trade-offs with Expired Items

Our model evaluates how the number of expected expired Product A and total costs are impacted as service level changes**.** Total costs include transportation costs, inventory costs, and COGS. **Figure 17** gives our sponsor company the ability to choose how they prioritize service level, total costs, and number of expected expired items. For each service level, the dots are optimal solutions and show the tradeoffs of total cost and number of expected expired items per week. The graph suggests that if the company wants to achieve a higher service level, the total costs will be higher in comparison to the total costs of a lower service level. For each time series, as the cost decreases the number of expected expired items also increases.

If the sponsor company decides to order every two weeks instead of every week, the inventory levels will increase and transportation costs will decrease. If inventory increases there is also a risk of more expired products. The company needs to decide what service level they want to operate at to make the trade-off of total costs and expired inventory.

5.6 Trade-offs with Emissions

The relationship with expired items and total emissions measured against service level and total costs are similar. Total costs include transportation costs, inventory costs, and COGS. Our model also evaluates how total emissions (kg CO_2) per week and total costs are impacted as service level changes**. Figure 18** gives our sponsor company the ability to choose how they prioritize service level, total costs, and total emissions (kg

CO_2) per week. For each service level, the dots are optimal solutions and show the tradeoffs of total cost and total emissions (kg CO_2) per week. The graph suggests that if the company wants to achieve a higher service level, the total costs will be higher in comparison to the total costs of a lower service level. For each time series, as the cost decreases the total emissions (kg CO_2) per week also increases.

Chapter 6: Conclusion

Our project analyzes the trade-offs between costs, mileage, service level, inventory strategy, and CO_2 emissions in a global food and beverage retailer's current network design. We analyzed the network design of a perishable product and evaluated which levers or variables can change (transportation mode, suppliers' locations, inventory) in their existing network, as well as what variables are constraints and cannot be changed (truck sizes, product specifications, DC locations). We explored how full truckload vs. less-than-truckload transportation impacts their network and consider new supplier locations. We created a network design model in Python that offers the sponsor company various solutions that highlight the trade-offs between costs, service level, and CO_2 emissions.

Key insights of this project are the following: (1) the company should utilize LTL transportation more than FTL; (2) there is a cost benefit of adding a third supplier to the network design; (3) if the company wants to achieve a higher service level, the total costs of inventory, transportation, and COGS will be higher in comparison to the total costs of a lower service level; and (4) for each service level, as the cost decreases the total emissions (kg CO_2) per week and expected number of expired items also increases.

Other key relationships are the following: (1) if COGS are considered in the model, the results will always pick the suppliers with the cheapest COGS until demand is fulfilled; (2) COGS are significantly higher costs compared to inventory and transportation costs; and (3) if orders are placed every two weeks instead of every week, the inventory levels will increase and transportation costs will decrease.

Our model has the capability to change almost any parameter and see how the outputs change the recommendations. For future areas to explore for this project, we recommend running the following scenarios:

1. Change the shelf-life of Product A from 70 days to 80+ days

2. If demand increases, how will the model change the recommendations about which suppliers to open

3. How will holding more safety stock at the suppliers impact the network design

4. Place orders to the suppliers every 3 or 4 weeks compared to 1 week

References

Ahumada, O., Villalobos, R. (2011). Operational model for planning the harvest and distribution of perishable agricultural products, Vol. 133, pp. 677-687.

Aung M.M., Chang Y. (2014). Traceability in a food supply chain: safety and quality perspectives, Food Control, vol. 39, no. 1, pp. 172–184.

DAT Trendlines: Trucking Industry Trends. (2022). DAT. https://www.dat.com/trendlines

Dong, M. (2001) Process Modeling, Performance Analysis and Configuration Simulation in Integrated Supply Chain Network Design, pp.110-154.

High Level Expert Forum - How to Feed the World in 2050. (2009). Office of the Director, Agricultural Development Economics Division Economic and Social Development Department pp.2

Huan, S.H., Sheoran, S.K. and Wang, G. (2004). A review and analysis of supply chain operations reference (SCOR) model, Supply Chain Management: An International Journal, Vol. 9, No. 1, pp.23–29.

Kitaw, D., Hailemariam, D., Garoma, T. (2011) Supply chain network design: opportunities for cost reduction, Zede Journal, vol. 28, pp. 65-82

Kumar, R., & Chandrakar, R. (2012). Overview of Green Supply Chain Management: Operation and Environmental Impact at Different Stages of the Supply Chain. 1(3), 6.

Le, T. (2022). *Coffee & Snack Shops in the US*. 52. https://www.ibisworld.com/industry-statistics/market-size/coffee-snack-shops-united-states/

Lee Y.H., Cho M.K., Kim S.J., Kim Y.B., (2002). Supply chain simulation with discrete–continuous combined modeling, Computers & Industrial Engineering, Vol. 43, pp. 375-392

Murthy, S., Gajanana, T., Mysore, (2009). Marketing and post-harvest losses in fruits: Its implications on availability and economy, Vol. 64.

Musavi, M.M., & Bozorgi-Amiri, A. (2017). A multi-objective sustainable hub location-scheduling problem for perishable food supply chain. Computers and Industrial Engineering, Vol 113, pp.766-778.

Paksoy, T., Weber G., Ozceylan, E., (2010), A multi-objective mixed integer programming model for multi echelon supply chain network design and optimization.

Ramezani M., Kimiagari A.M., Karimi, B., (2014), , Appl. Math. Model., 38 (15–16), pp. 4099-4119.

Terzi, S., Cavalieri, S. (2004) ‘Simulation in the supply chain context: a survey’, Computers in Industry, Vol. 53, No. 1, pp.3–16.

Turi, A., Goncalves, G., & Mocan, M., (2014). Challenges and Competitiveness Indicators for the Sustainable Development of the Supply Chain in Food Industry. *Procedia - Social and Behavioral Sciences*, Vol 124, pp.133–141.

Van der Vorst, J. G. A. J., Tromp, S.-O., & Zee, D.-J. van der. (2009). Simulation modeling for food supply chain redesign; integrated decision making on product quality, sustainability and logistics. *International Journal of Production Research*, *47*(23), pp. 6611–6631.

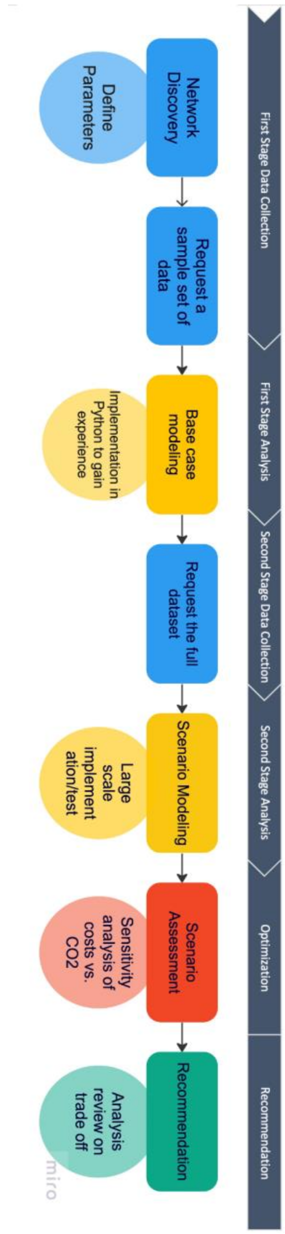
Woods, R. (2015). Freight to Plate. *Air Cargo World*, *105*(7), pp. 19–22.

Yakavenka, V., Mallidis, I., Vlachos, D., Iakovou, E., & Eleni, Z. (2019). Development of a multi-objective model for the design of sustainable supply chains: the case of perishable food products. Annals of Operations Research. pp. 595

Appendix

Figure 2

Project Flow



Note. **Figure 2** shows the process flow of data collection, analysis and modeling, scenario assessment, and a recommendation.