Optimization of Cost and Carbon Emissions in a Multi-Echelon Distribution Network

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ABSTRACT

Over the past decade, the oilfield services industry has experienced two major trends: the drive to reduce costs and the push for sustainability. In this context, our sponsor company seeks to optimize the distribution of materials and supplies in their global network, while considering both distribution costs and greenhouse gas (GHG) emissions. Our project has three objectives. The first is to develop an optimal transportation plan for materials and supplies – through the network of suppliers, manufacturing centers, distribution centers, and field warehouses – simultaneously minimizing distribution costs and GHG emissions. The second objective is to estimate the potential cost and GHG emissions reductions the company could achieve by bypassing the manufacturing centers for the eligible parts. Finally, our project aims to provide a deep understanding of the trade-offs between distribution costs, GHG emissions, and lead time. To achieve these objectives, we built a Mixed-Integer Linear Programming model that minimizes distribution and GHG emissions costs under demand and maximum lead time constraints. Our model provides an optimal transportation plan that recommends the quantity and mode of transport throughout the echelons of the network for all parts in scope. Our results show that bypassing the manufacturing centers could lead to a 3.7% reduction in distribution costs and a 1.7% reduction in GHG emissions. Moreover, our results show that most of the distribution cost reduction is due to the reduction in duties and that a small number of parts accounts for most of the cost savings. Finally, by varying the weight assigned to the distribution cost and to the GHG emissions cost in the objective function, we demonstrate that the company can achieve quick wins in emissions reduction.

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Boping

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

1.1 Motivation and Background

In the last decade, two significant trends have shaped the oilfield services industry. The first one is greater pressure on costs: Since oil prices began to decline in 2014, falling revenues have eroded oilfield services companies' margins (Dickson et al., 2019), forcing them to tightly control costs. The second trend is greater attention to sustainability: Many companies in the industry are acting on greenhouse gas (GHG) emissions and publicly announcing their program objectives and achievements (Roy, n.d.).

Like many other actors in the oil and gas industry, our sponsor company publicly made GHG reduction commitments. Its goal is to achieve net-zero GHG emissions by 2050 and to reduce by 30% its Scope 3 emissions by 2030. Scope 3 emissions are defined as emissions that "are a consequence of the activities of the company but occur from sources not owned or controlled by the company. Some examples of Scope 3 activities are extraction and production of purchased materials, transportation of purchased fuels, and use of sold products and services" (World Resources Institute & World Business Council for Sustainable Development, 2004, p.25).

In the context shaped by these two trends, initiatives that reduce costs and GHG emissions, especially Scope 3 emissions, are highly relevant for the sponsor company. The optimization of the end-to-end distribution of materials and supplies is one of them. This will be the subject of our project.

Our sponsor company delivers products and services to oil and gas operators in over 120 countries. Its portfolio of core equipment and services ranges from reservoir characterization to well construction and production systems. The company manufactures its tools and equipment in over 50 manufacturing centers around the world. It relies on hundreds of suppliers and four main international distribution centers (DCs). Those numbers show the scale and complexity of the supply chain network of the sponsor company.

Materials & Supplies (M&S) refer to spare parts needed for the maintenance of assets. M&S flow from the suppliers to the manufacturing centers, then to the DCs, then to the field warehouses. In 2021, the company conducted a network design study aiming to minimize the distribution cost of M&S from the manufacturing centers to the field warehouses. This study confirmed that the current number and location of DCs were optimal and recommended a transportation plan for M&S, i.e., the quantity and mode of transport of each part moving from one node of the network to the other. Today, the company is interested in defining a transportation plan that goes further up the supply chain to include the suppliers, as it sees further opportunities for optimization. Indeed, some M&S transit unnecessarily through the manufacturing centers, without any added value. Additionally, as sustainability has become more prominent in the company's strategy, the company is interested in making its transportation plans not only more cost-efficient, but also more sustainable. By optimizing the transportation plans of M&S through the existing end-to-end network, the company expects to reduce cost and GHG emissions, which would help it reach its publicly stated Scope 3 emissions reduction goal.

In Section 1.2, we describe the sponsor company's current distribution network. Next, we define the problem statement and the project objectives.

1.2   Current State

The sponsor company distributes M&S through a three-echelon multi-commodity network composed of suppliers, manufacturing centers, DCs, and field warehouses. An illustrative example of the distribution network is shown in Figure 1.

The *suppliers* provide M&S to the manufacturing centers. Depending on the agreed-upon Incoterms (set of internationally recognized rules defining the responsibilities of buyers and sellers), the transportation to the manufacturing centers is either managed by the company or by supplier.

Figure 1

Distribution Network at the Sponsor Company
table 7
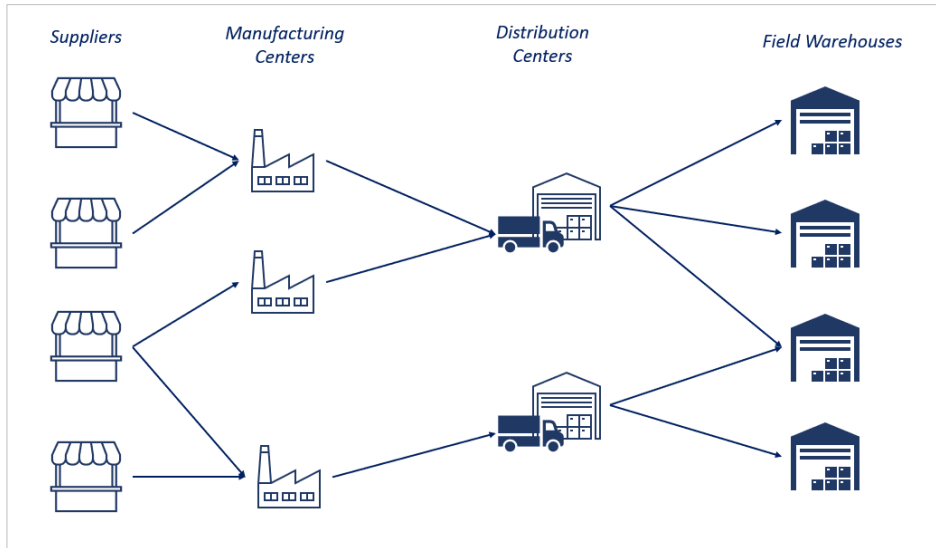
The *manufacturing centers* are specialized by technology such as formation evaluation tools or drilling tools. While some M&S are used to build tools in the manufacturing centers, most are sent to the DCs either directly or after inspection. Each manufacturing center sends M&S to a predetermined DC, usually the closest one. For example, the Stonehouse manufacturing center in the United Kingdom sends M&S to Rotterdam DC, in the Netherlands.

The sponsor company currently has four main *DCs* located in Houston, Rotterdam, Dubai, and Singapore. Each DC serves the field warehouses located in a defined area, e.g., Houston DC serves the warehouses located in North and South America. The DCs perform two main roles. First, they consolidate the cargo heading to the same destination to reduce transportation costs. The rules of consolidation are defined by the Field Logistics Service Agreement, which is an internal document that specifies the rules for consolidation for each destination country (e.g., one shipment per week, one shipment every two weeks, and so forth). The second role of DCs is to hold inventory for M&S that have a stable demand to reduce lead time. These M&S are referred to as Buy-To-Stock parts (BTS). The M&S that do not have stable

demand are referred to as Buy-To-Order parts (BTO). For such parts, no inventory is held in the DCs: for each purchase order placed by a field warehouse, the DC places a corresponding purchase order to the manufacturing center.

The *field warehouses* generate the demand for M&S by placing internal purchase orders to the DCs. Figure 2 shows the field warehouses demand in terms of volume of transactions (count of delivery lines) for 2022, aggregated by country. The top five countries with the highest demand are Saudi Arabia, Oman, Indonesia, Qatar, and Ecuador.

Figure 2

Volume of Transactions (Count of Delivery Lines) from DCs to Field Warehouses (2022)

To move M&S through the different echelons of the network, the sponsor company negotiated transportation rates with its logistics providers for four modes of transportation:

- Air freight: used for international shipments.

- Express courier: door-to-door service for parcels weighing less than 70 kg; used for international shipments; usually faster than air freight.

- Full Truck Load (FTL): used for domestic shipments and some international shipments.

- Less than Truck Load (LTL): used mainly for domestic shipments in the US.

1.3 Problem Statement and Research Questions

As mentioned in Section 1.2, the company has identified M&S that transit through the manufacturing centers without any added value. Bypassing the manufacturing centers for these M&S as shown in Figure 3 could generate savings for the company in terms of cost (transportation and duties) and GHG emissions. Considering the current nodes of the network (suppliers, manufacturing centers, DCs, and field warehouses), and while allowing the bypass of the manufacturing centers for the eligible parts, the problem statement of this project is: How to optimize the M&S transportation plan within the network in terms of distribution cost and GHG emissions?

Figure 3

Bypass of the Manufacturing Centers
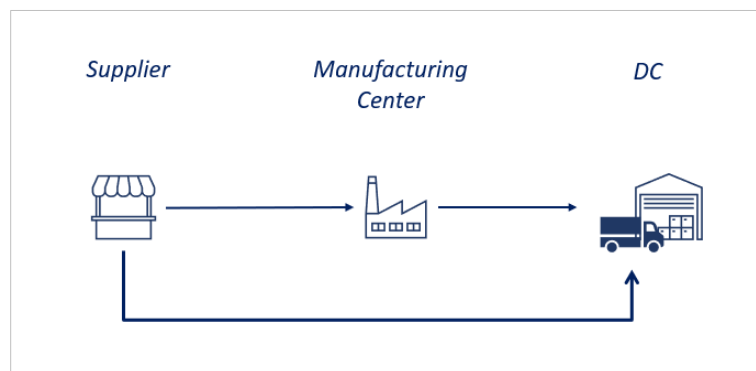
In particular, our research questions are:

1. What is the optimal transportation plan for M&S through the network of suppliers, manufacturing centers, DCs, and field warehouses?

2. What reductions could the company achieve in terms of distribution cost and GHG emissions by bypassing the manufacturing centers for eligible parts?

3. What are the trade-offs for the company between cost, GHG emissions, and lead time?

1.4   Project Objectives

Our project provides the company with a mathematical optimization model that minimizes the M&S distribution cost and GHG emissions within its current distribution network. This model enables us to run a sensitivity analysis that can provide a better understanding of the trade-offs between the objectives.

The deliverables to the company include:

1. A distribution optimization model that can be plugged into the company's solver, with the capability to adapt to different objectives

2. An optimal M&S transportation plan that minimizes cost and GHG emissions without changing facility locations or functions

3. An estimation of the cost savings to help the company make better sourcing and transportation decisions

4. A projection of GHG emissions savings that will help the company better understand the trade-offs between objectives so it can pick the most appropriate solution to implement

We expect that the model will generate an optimal transportation plan that specifies which suppliers, manufacturing centers, and DCs should be involved in fulfilling the demand of each field warehouse for each M&S. Additionally, we aim to show the trade-offs between distribution cost, GHG emissions, and lead time. If the company would like to prioritize one objective over the others, it will be crucial for them to understand these trade-offs to make informed decisions.

2. STATE OF THE ART

In this section, we first introduce the three levels of transportation decisions and present how mathematical modeling was used in transportation planning decisions. Next, we give an overview of how GHG emissions were factored in transportation planning. Finally, we present an overview on how companies calculate GHG emissions.

2.1 Transportation Planning

Schmidt and Wilhelm (2000) categorize multi-national logistics networks decisions into three categories: strategic, tactical, and operational. "The strategic level designs the logistics network, including prescribing facility locations, production technologies and plant capacities. The tactical level prescribes material flow management policies, including production levels at all plants, assembly policy, inventory levels, and lot sizes. The operational level schedules operations to assure in-time delivery of final products to customers" (p.1501). Since our project does not aim at changing the number of facilities or their locations, we define the project's decisions as tactical decisions.

Mangiaracina et al. (2015) published a review of the distribution network design literature. Among 86 papers based on a quantitative model/approach, 68 applied Mixed-Integer Linear Programming (MILP) models to minimize distribution costs. MILP has been widely perceived as an effective approach for solving transportation planning and supply chain network design problems. MILP enables researchers or companies to convert real-world supply chain models into a mathematical formulation, visualizing the optimal planning solution across all network parties. It also allows them to extend the model to suit specific research interests or supply chain considerations, such as inventory policies, transshipment decisions, order fulfillment goals, shipping schedules, and planning horizons.

Kharodawala et al. (2022) used a single-objective MILP model to model a multi-modal, multi-echelon, multi-period transportation planning problem. This problem shares the multi-echelon and multi-modal aspects with our project's setting. The results showed that using MILP to model the transportation

planning problem with a single objective is an effective approach. Although the multi-commodity aspect was not considered in the problem, the authors mentioned that the model could be used as a base for multi-commodity transportation planning problems.

2.2   Factoring GHG Emissions in Transportation Problems

As environmental awareness and legislative pressure increased, companies and researchers started to consider GHG emissions in their transportation planning models using different approaches. One approach is to set the emissions as a constraint. For example, Mirzapour Al-e-Hashem & Rekik (2014) proposed a MILP model to address a multi-commodity, multi-period inventory routing optimization problem with the consideration of emissions as a constraint. The authors performed a sensitivity analysis by tightening the constraints on the emissions levels and observing the impact on the transportation cost and the inventory cost. This approach allows companies to visualize the financial impact of different emissions thresholds.

Recently, Demir et al. (2019) presented an analysis using a bi-objective model to minimize the total transportation costs and the GHG emissions for an intermodal freight transportation case study from hinterland intermodal transportation in Europe. They presented three multi-objective methods. The first method, the basic weight method, assigns to each objective function a weighting coefficient, then minimizes the weighted sum of the objectives. The second method, the weighting method with normalization, is a variation of the first one: the objective functions are normalized to take values between 0 and 1. The last method presented by the authors is the epsilon-constraint method, where one objective function is optimized while the others are converted into constraints by imposing an upper bound, similar to the approach followed by Mirzapour Al-e-Hashem & Rekik (2014) mentioned earlier.

A final approach to incorporate GHG emissions into transportation problems is to assign a cost to them. Once the emissions and distribution costs are both expressed in monetary terms, they can be added to the same objective function. For example, Elhedhli and Merrick (2012) formulated a MILP model

for a green network design problem. The objective function in their model included emissions costs and distribution costs. Similarly, Treitl et al. (2012) used this approach in an inventory distribution case study from the petrochemical industry. The authors used in their numerical analysis the European Union Emissions Trading System (EU ETS) carbon price.

2.3 Calculating Scope 3 Emissions

Greenhouse Gas Protocol Technical Guidance for Calculating Scope 3 Emissions (World Resources Institute & World Business Council for Sustainable Development, 2013) provides guidelines on the calculation of Scope 3 emissions resulting from transportation. According to these guidelines, companies may use three methods. The first is the fuel-based method. It requires determining the amount of fuel consumed by transport providers and applying the appropriate emission factor. The second method, the spend-based method, involves determining the fuel spending on each mode of transport and applying secondary emissions factors. Finally, the distance-based method involves determining the mass, distance, and mode of each shipment, then applying a mass-distance emission factor for each vehicle or mode used.

In the distance-based method, the emissions are calculated by the formula: mass of goods transported x distance traveled × emissions factor of transport mode or vehicle type. Emissions factors are usually expressed in kilograms of carbon dioxide equivalent per tonne-kilometer (noted, kg CO_2e / t.km). Tonne-kilometer is a unit of measure representing one metric ton of goods transported over 1 kilometer.

3.   DATA AND METHODOLOGY

In this section, we present the data and methodology for our project by describing the data

collection and processing. Then, we present the model assumptions, formulation, and implementation.

3.1   Data Collection and Processing

Table 1 presents the collected data and its use in our mathematical model.

Table 1

Data Collection

Source Datasets	Derived Datasets	Ultimate Use
DC shipments	Field warehouses demand	Demand constraints
	Average shipment size from DCs to field warehouses	Transportation cost
	DCs to field warehouses feasible combinations	Flow variables
	Selling prices from the DCs	Duties cost
Manufacturing centers outbound data	Average shipment size from manufacturing centers to DCs	Transportation cost
	Selling prices from the manufacturing centers	Duties cost
Manufacturing centers source data	Average shipment size from suppliers to manufacturing centers	Transportation cost
	Suppliers to manufacturing centers feasible combinations	Flow variables
	Selling prices from the suppliers	Duties cost
Negotiated transportation rates and lead times		Transportation cost Lead time constraints
List of parts eligible to bypass the manufacturing centers	Suppliers to DCs feasible combinations	Flow variables
Weight of parts		GHG emissions Transportation cost
GPS coordinates of suppliers, manufacturing centers, DCs, and field warehouses	Distances between the nodes of each echelon	GHG emissions

The source datasets were shared by the sponsor company in .csv format. We then cleaned and

preprocessed the data in Python. Specifically, we eliminated unnecessary columns, standardized the

spelling of some categorical values (e.g., the terms FTL, TL, Road-FTL all relate to the same mode: FTL),

and ignored rows with null values when appropriate. Next, we excluded from the data the bottom quartile of field warehouse countries in terms of demand quantity. We thus reduced the number of field warehouse countries from 95 to 71 while capturing 99.99% of the demand quantity.

Due to data unavailability for the full-scale network, we limit the scope of the analysis to one manufacturing center, P9036, located in Houston, TX. This manufacturing center was chosen not only because of being one of the largest manufacturing centers in the company, but also for the quality of the data. Subsequently, we derived the list of parts with more than five transactions in that manufacturing center in 2022. The final list of parts in scope included 1,870 parts, representing 82% of the transaction lines. In the remaining data, shipments from the selected manufacturing center to Houston and Dubai DCs represented 99.75% of delivery lines. Therefore, we opted to exclude the other DCs from our model.

3.2   Model Assumptions

The goal of our project is to minimize distribution costs and GHG emissions resulting from the distribution of M&S. As part of the distribution cost, we consider transportation cost and duties cost. In the following paragraphs, we describe our model assumptions for the transportation cost, duties cost, and GHG emissions cost, as well as some additional assumptions.

For each arc and mode of transportation, we computed the *transportation cost* as the product of the weight of the part, the cost per unit of weight, and the quantity of the part transported on the corresponding arc via the designated mode of transport. To obtain the cost per unit of weight, we computed the average shipment size for each origin-destination-mode combination and derived the cost from the negotiated transportation rates tables. The average shipment sizes (per mode and lane) are considered constant compared to 2022. We assume that bypassing the manufacturing centers will not affect the average shipment size from manufacturing centers to DCs for the remainder of the parts.

The *duties cost* on an arc of the network is the product of the duty rate, the selling price of the part, and the quantity of the part shipped on that arc. We assume country-level duty rates regardless of

the Harmonized Tariff System codes that apply to specific parts. The percentage of duties is applied to the selling price instead of applying to the Cost, Insurance, and Freight (CIF) price or to the Free On Board (FOB) price. The country of departure is used instead of the country of origin of the part.

Regarding the GHG emissions, we consider only Scope 3 emissions resulting from transportation. We use the distance-based method described in Section 2.3 that calculates the carbon emissions as the product of mass, distance, and carbon-equivalent intensity factors for each mode. We use the carbon-equivalent intensity factors derived from the GLEC Framework for Logistics Emissions Accounting and Reporting Version 2.0 (Smart Freight Centre, 2019) and presented in Table 2. The distances for FTL and LTL are obtained using Google Maps API. We compute the distances for air freight through the great circle formula (straight-line distances). Although express courier could use air, road, or a combination of both, in the context of our project, this service is used for international shipments, so we assume the same intensity factor as for air freight and we use the great circle formula to compute distances.

Table 2

Carbon-Equivalent Intensity Factors per Mode of Transportation Used in our Model

Mode	CO_2e Intensity Factor [kg CO_2e / t.km]
Air freight	0.920
Express courier	0.920
LTL	0.140
FTL	0.093

Note. Data from the GLEC Framework for Logistics Emissions Accounting and Reporting Version 2.0 (Smart Freight Centre, 2019).

The *GHG emissions cost* is calculated as the GHG emissions in tonne-kilometers times the cost of carbon. Since the sponsor company does not have an internal carbon pricing scheme, we use the European Carbon Allowance (EUA) spot price[1].

Other model assumptions are listed below:

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[1] Retrieved on April 4, 2023, from https://www.eex.com/en/market-data/environmentals/spot

- The demand of the field warehouses for each part is the same as 2022 level.

- The field warehouses are aggregated at the country level. The location corresponding to a destination country is set as the location of the main airport used in that country (based on the weight the company shipped via that airport in 2022). For example, we used the location of Dammam Airport for Saudi Arabia, Stavanger Airport for Norway, and Jakarta Airport for Indonesia.

- Flows are conserved in the manufacturing centers and DCs (i.e., inbound quantities equal outbound quantities for each part).

- Purchases are under Ex-Works Incoterms. Since the suppliers' pick-up locations were not available in the purchase order data, they were approximated with the suppliers' main addresses.

Appendix A presents additional assumptions related to the data.

3.3 Model Formulation

Building the mathematical model consists of defining our decision variables, objective function, and constraints. These will be discussed in Sections 3.4.2, 3.4.3, and 3.4.4, respectively. First, we define the sets and parameters used in our mathematical formulation.

3.3.1 Sets and Parameters

Tables 3 and 4 present the sets and parameters used in our mathematical formulation.

Table 3

List of Sets Used in the Mathematical Formulation

Symbol	Definition
S	Set of suppliers
M	Set of manufacturing centers
D	Set of DCs
F	Set of field warehouses
P_{BTS}	Subset of Buy-To-Stock parts (i.e., parts stocked in the DCs).
P_{BTO}	Subset of Buy-To-Order parts (i.e., parts not stocked in the DCs).
P	Set of all parts (i.e., $P = P_{BTS} \cup P_{BTO}$)
P_b	Subset of parts eligible to bypass the manufacturing centers.
V	Set of modes: Air freight, express courier, LTL, FTL

Table 4

List of Parameters Used in the Mathematical Formulation

Symbol	Definition	Unit
c_{sm}^v	Average transportation cost per unit of weight moving from supplier s to manufacturing center m using mode v, with $s \in S, m \in M, v \in V$.	[\$/kg]
c_{md}^v	Average transportation cost per unit of weight moving from manufacturing center m to DC d using mode v, with $m \in M, d \in D, v \in V$.	[\$/kg]
c_{df}^v	Average transportation cost per unit of weight moving from DC d to field warehouse f using mode v, with $d \in D, f \in F, v \in V$.	[\$/kg]
c_{sd}^v	Average transportation cost per unit of weight moving from supplier s to DC d using mode v, with $s \in S, d \in D, v \in V$.	[\$/kg]
w^p	Weight of part $p \in P$.	[kg]
q_{ij}	Percentage of duties from node i to node j, with $i, j \in S \cup M \cup D \cup F$ such that $i \neq j$.	[%]
s_i^p	Selling price of part p from node i, with $i \in S \cup M \cup D, p \in P$.	[\$/unit]
d_f^p	Demand of part p from field warehouse f, with $p \in P, f \in D$.	[unit]
t_{md}^v	Lead time from manufacturing center m to DC d using mode v, with $m \in M, d \in D, v \in V$.	[days]
t_{df}^v	Lead time from DC d to field warehouse f using mode v, with $d \in D, f \in F, v \in V$.	[days]
t_{sd}^v	Lead time from supplier s to DC d using mode v, with $s \in S, d \in D, v \in V$.	[days]
T_{BTO}	Maximum lead time allowed for Buy-To-Order parts $p \in P_{BTO}$.	[days]
T_{BTS}	Maximum lead time allowed for Buy-To-Stock parts $p \in P_{BTS}$.	[days]
l_{ij}^v	Distance from node i to node j using mode v, with $i, j \in S \cup M \cup D \cup F, v \in V$.	[km]
e^v	GHG emissions intensity factors for mode $v \in V$.	[kg CO₂e/t.km]
M	A large number.	-

3.3.2 Decision Variables

The decision variables used in our model are presented in Table 5.

Table 5

List of Decision Variables Used in the Mathematical Formulation.

Symbol	Definition
x_{sm}^{pv}	Quantity of part p moving from supplier s to manufacturing center m using mode v, with $s \in S, m \in M, p \in P, v \in V$
y_{md}^{pv}	Quantity of part p moving from manufacturing center m to DC d using mode v, with $m \in M, d \in D, p \in P, v \in V$
z_{df}^{pv}	Quantity of part p moving from DC d to field warehouse f using mode v, with $d \in D, f \in F, p \in P, v \in V$
u_{sd}^{pv}	Quantity of part p moving from supplier s to D d using mode v, with $s \in S, d \in D, p \in P_b, v \in V$
$\alpha_{mdf}^{pvv'}$	1, if part p is routed using mode v from manufacturing center m to DC d, and using mode v' from DC d to field warehouse f. 0, otherwise. $m \in M, d \in D, f \in F, p \in P, v \in V, v' \in V$.
$\beta_{sdf}^{pvv'}$	1, if part p is routed using mode v from supplier s to DC d, and using mode v' from DC d to field warehouse f. 0, otherwise. $s \in S, d \in D, f \in F, p \in P, v \in V, v' \in V$.
γ_{md}^{pv}	1, if there is a flow of part p using mode v from manufacturing center m to field warehouse f. 0, otherwise. $m \in M, d \in D, p \in P, v \in V$.
δ_{df}^{pv}	1, if there is a flow of part p using mode v from DC d to field warehouse f. 0, otherwise. $d \in D, f \in F, p \in P, v \in V$.
ε_{sd}^{pv}	1, if there is a flow of part p using mode v from supplier s to field warehouse f. 0, otherwise. $s \in S, d \in D, p \in P_b, v \in V$

3.3.3 Objective Function

The objective function (1) minimizes the sum of the transportation (Z_{TC}), duties (Z_{DC}), and GHG emissions costs (Z_{GHGC}).

$$\text{minimize } Z_{TC} + Z_{DC} + Z_{GHGC} \tag{1}$$

where:

$$Z_{TC} = \sum_{s \in S} \sum_{m \in M} \sum_{p \in P} \sum_{v \in V} c_{sm}^v \cdot w^p \cdot x_{sm}^{pv} + \sum_{m \in M} \sum_{d \in D} \sum_{p \in P} \sum_{v \in V} c_{md}^v \cdot w^p \cdot y_{md}^{pv}$$

$$+ \sum_{d \in D} \sum_{f \in F} \sum_{p \in P} \sum_{v \in V} c_{df}^v \cdot w^p \cdot z_{df}^{pv} + \sum_{s \in S} \sum_{d \in D} \sum_{p \in P} \sum_{v \in V} c_{sd}^v \cdot w^p \cdot u_{sd}^{pv} \tag{2}$$

$$Z_{DC} = \sum_{s \in S} \sum_{m \in M} \sum_{p \in P} \sum_{v \in V} q_{sm} \cdot s_s^p \cdot x_{sm}^{pv} + \sum_{m \in M} \sum_{d \in D} \sum_{p \in P} \sum_{v \in V} q_{md} \cdot s_m^p \cdot y_{md}^{pv}$$

$$+ \sum_{d \in D} \sum_{f \in F} \sum_{p \in P} \sum_{v \in V} q_{df} \cdot s_d^p \cdot z_{df}^{pv} + \sum_{s \in S} \sum_{d \in D} \sum_{p \in P} \sum_{v \in V} q_{sd} \cdot s_s^p \cdot u_{sd}^{pv} \tag{3}$$

$$Z_{GHGC} = \sum_{s \in S} \sum_{m \in M} \sum_{p \in P} \sum_{v \in V} e^v \cdot l_{sm}^v \cdot w^p \cdot x_{sm}^{pv} + \sum_{m \in M} \sum_{d \in D} \sum_{p \in P} \sum_{v \in V} e^v \cdot l_{md}^v \cdot w^p \cdot y_{md}^{pv}$$

$$+ \sum_{d \in D} \sum_{f \in F} \sum_{p \in P} \sum_{v \in V} e^v \cdot l_{df}^v \cdot w^p \cdot z_{df}^{pv} + \sum_{s \in S} \sum_{d \in D} \sum_{p \in P} \sum_{v \in V} e^v \cdot l_{sd}^v \cdot w^p \cdot u_{sd}^{pv} \tag{4}$$

3.3.4 Constraints

The constraints to our optimization model are listed below.

Demand constraints:

$$\sum_{d \in D} \sum_{v \in V} z_{df}^{pv} \geq d_f^p, \qquad \forall\, p \in P, f \in F \tag{5}$$

Maximum lead time constraints:

$$(t_{md}^v + t_{df}^{v'}) \cdot \alpha_{mdf}^{pvv'} \leq T_{BTO}, \qquad \forall\, m \in M, d \in D, f \in F, p \in P_{BTO}, v \in V, v' \in V \tag{6}$$

$$(t_{sd}^v + t_{df}^{v'}) \cdot \beta_{sdf}^{pvv'} \leq T_{BTO}, \qquad \forall\, s \in S, d \in D, f \in F, p \in P_{BTO}, v \in V, v' \in V \tag{7}$$

$$t_{df}^v \cdot \delta_{df}^{pv} \leq T_{BTS}, \qquad \forall\, d \in D, f \in F, p \in P_{BTS}, v \in V \tag{8}$$

Conservation of flow constraints:

$$\sum_{s \in S}\sum_{v \in V} x_{sm}^{pv} - \sum_{d \in D}\sum_{v \in V} y_{md}^{pv} = 0, \qquad \forall\, m \in M, p \in P \tag{9}$$

$$\sum_{m \in M}\sum_{v \in V} y_{md}^{pv} + \sum_{s \in S}\sum_{v \in V} u_{sd}^{pv} - \sum_{f \in F}\sum_{v \in V} z_{df}^{pv} = 0, \qquad \forall\, d \in D, p \in P \tag{10}$$

Linking constraints:

$$y_{md}^{pv} - M \cdot \gamma_{md}^{pv} \leq 0 \qquad \forall\, m \in M, d \in D, p \in P, v \in V \tag{11}$$

$$z_{df}^{pv} - M \cdot \delta_{df}^{pv} \leq 0 \qquad \forall\, d \in D,\ f \in F,\ p \in P,\ v \in V \tag{12}$$

$$u_{sd}^{pv} - M \cdot \varepsilon_{sd}^{pv} \leq 0 \qquad \forall\, s \in S, d \in D, p \in P, v \in V \tag{13}$$

$$\alpha_{mdf}^{pvv'} \geq \gamma_{md}^{pv} + \delta_{df}^{pv'} - 1 \qquad \forall\, m \in M, d \in D, f \in F, p \in P, v \in V, v' \in V \tag{14}$$

$$\alpha_{mdf}^{pvv'} \leq \gamma_{md}^{pv} \qquad \forall\, m \in M, d \in D, f \in F, p \in P, v \in V, v' \in V \tag{15}$$

$$\alpha_{mdf}^{pvv'} \leq \delta_{df}^{pv} \qquad \forall\, m \in M, d \in D, f \in F, p \in P, v \in V, v' \in V \tag{16}$$

$$\beta_{sdf}^{pvv'} \geq \varepsilon_{sd}^{pv} + \delta_{df}^{pv'} - 1 \qquad \forall\, s \in S, d \in D, f \in F, p \in P, v \in V, v' \in V \tag{17}$$

$$\beta_{sdf}^{pvv'} \leq \varepsilon_{sd}^{pv} \qquad \forall\, s \in S, d \in D, f \in F, p \in P, v \in V, v' \in V \tag{18}$$

$$\beta_{sdf}^{pvv'} \leq \delta_{df}^{pv'} \qquad \forall\, s \in S, d \in D, f \in F, p \in P, v \in V, v' \in V \tag{19}$$

Domain definition constraints:

$$x_{sm}^{pv} \geq 0, \qquad \forall\, s \in S, m \in M, p \in P, v \in V \tag{20}$$

$$y_{md}^{pv} \geq 0, \qquad \forall\, m \in M, d \in D, p \in P, v \in V \tag{21}$$

$$z_{df}^{pv} \geq 0, \qquad \forall\, d \in D, f \in F, p \in P, v \in V \tag{22}$$

$$u_{sd}^{pv} \geq 0, \qquad \forall\, s \in S, d \in D, p \in P, v \in V \tag{23}$$

$$\alpha_{mdf}^{pvv'} \in \{0,1\}, \qquad \forall\, m \in M, d \in D, f \in F, p \in P, v \in V, v' \in V \tag{24}$$

$$\beta_{sdf}^{pvv'} \in \{0,1\}, \qquad \forall\, s \in S, d \in D, f \in F, p \in P, v \in V, v' \in V \tag{25}$$

$$\gamma_{md}^{pv} \in \{0,1\}, \qquad \forall\, m \in M, d \in D, p \in P, v \in V \tag{26}$$

$$\delta_{df}^{pv} \in \{0,1\}, \qquad\qquad \forall\, d \in D, f \in F, p \in P, v \in V \qquad\qquad (27)$$

$$\varepsilon_{sd}^{pv} \in \{0,1\}, \qquad\qquad \forall\, s \in S, d \in D, p \in P, v \in V \qquad\qquad (28)$$

Constraints (5) ensure the satisfaction of the demand of each field warehouse. Constraints (6) establish the maximum lead time allowed for parts stocked in the manufacturing centers, whereas Constraints (7) state the maximum lead time allowed for parts flowing directly from suppliers to DCs. Constraints (8) establish the maximum lead time allowed for parts stocked in the DCs. Flow balance constraints in the manufacturing centers and DCs are included in Constraints (9) and (10), respectively. Constraints (11) to (19) are linking constraints. Finally, the domain of each decision variable is defined in Constraints (20) to (28).

3.4   Model Implementation

In the computational implementation of the MILP model (1)-(28), we only define decision variables and constraints for the currently available transportation lanes. For example, we do not create decision variables for the arc Houston DC to Norway via FTL since there is no road between these two nodes. To achieve this, we create feasibility matrices for each echelon of the network, then we define the decision variables and constraints only for the combinations that belong to these feasibility matrices. The logic for the generation of the feasibility matrices is described in Table 6.

The resulting model was implemented in Python, using Gurobi 10.0.1 as a solver. The inputs to our code are .csv files generated from the data processing step. The output of our code is Excel files providing:

- A transportation plan that recommends the quantity and mode of transport throughout the echelons of the network for all parts in scope

- An estimation of the distribution costs and GHG emissions resulting from that plan

This implementation allows to easily vary the parameters such as the parts in scope and the maximum allowed lead time. It also allows to vary the weight of each objective (distribution cost and emissions), making it easy to conduct sensitivity analysis.

Table 6

Logic for the Generation of the Feasibility Matrices.

Echelon	Logic
DCs to field warehouses	For all parts-field warehouses combinations with demand: • All origin-destination combinations for air freight and express courier are feasible • Limited origin-destination feasible combinations for LTL and FTL (based on geography)
Manufacturing center to DCs	For all parts in scope and all origin-destination combinations: • Only LTL and FTL are feasible for US to US • All modes are feasible for US to non-US
Suppliers to manufacturing center	For all parts in scope, and for supplier-part combinations as per the purchasing data: • Only LTL and FTL are feasible for US to US • Air freight and express courier are feasible for US to non-US
Suppliers to DCs	For all parts eligible to bypass the manufacturing centers, and for supplier-part combinations as per the purchasing data: • Only LTL and FTL are feasible for US to US • Air freight and express courier are feasible for US to non-US and non-US to US

4. RESULTS

In this section, we summarize the results of our numerical analysis. We first present the results for the new policy "bypassing the manufacturing centers" compared to the baseline scenario (i.e., where bypassing is not allowed). We then conduct a sensitivity analysis on the relative importance of the emissions cost compared to the distribution cost. Finally, we present a sensitivity analysis by restricting the maximum lead time allowed.

4.1 Bypassing the Manufacturing Centers

In the "bypass scenario", the parts that do not require either inspection or value-added activity in the manufacturing centers are allowed to be shipped directly from the suppliers to the DCs. Table 7 presents the costs (in thousands of US dollars) and emissions for both the baseline and the bypass scenarios.

Table 7

Annual Savings for the Bypass Scenario

	Baseline	Bypass	Savings	Relative Savings
Distribution Cost	3,286	3,164	121	3.7%
Transportation Cost	1,412	1,393	19	1.3%
Duties Cost	1,874	1,771	102	5.5%
Emission Cost	190	187	3	1.7%
Total Cost	3,476	3,351	125	3.6%
Emissions (tonne CO2e)	1,814	1,782	32	1.7%

Note. Costs in thousands of US dollars

Table 7 shows that the bypass scenario results in 3.6% savings in the total cost and in 1.7% savings in GHG emissions. The cost reduction is primarily driven by a reduction in the duties cost (-5.5%). By analyzing the parts with the highest savings (shown in Table 8), we observe that there are 10 parts that account for 92.4% of the total savings.

Table 8

Top 10 Parts Generating the Highest Annual Savings in the Bypass Scenario

Part ID	Savings	Cumulated Savings
S-400521	53.2	42.6%
H433764	18.4	57.4%
H433563	13.1	67.9%
H433630	12.9	78.2%
T1061015	5.9	83.0%
P498119	3.5	85.8%
T1061016	2.6	87.8%
H433708	2.2	89.6%
T1057150	2.0	91.2%
S-285740	1.5	92.4%

Note. Costs in thousands of US dollars

As an illustration, we followed the path of the part S-400521 to show the mechanisms through which savings are generated. Figure 4 shows the path of the part in both the baseline and the bypass scenarios. In the bypass scenario, the part does not flow through Houston DC, avoiding the 20% duty rate that applies for China to US imports. As shown in Figure 5, most of the cost savings for part S-400521 result from a reduction in duty cost.
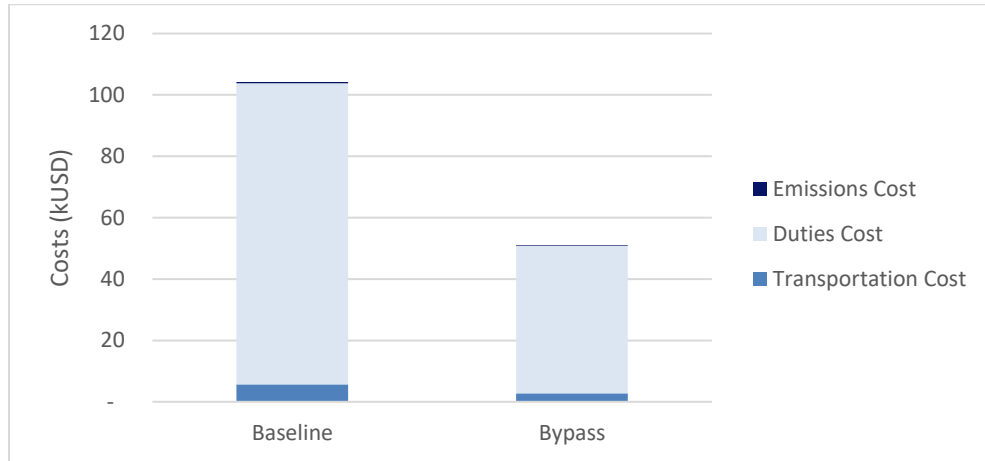
Figure 4

Example of the Path of Part S-400521 in the Baseline and Bypass Scenarios.
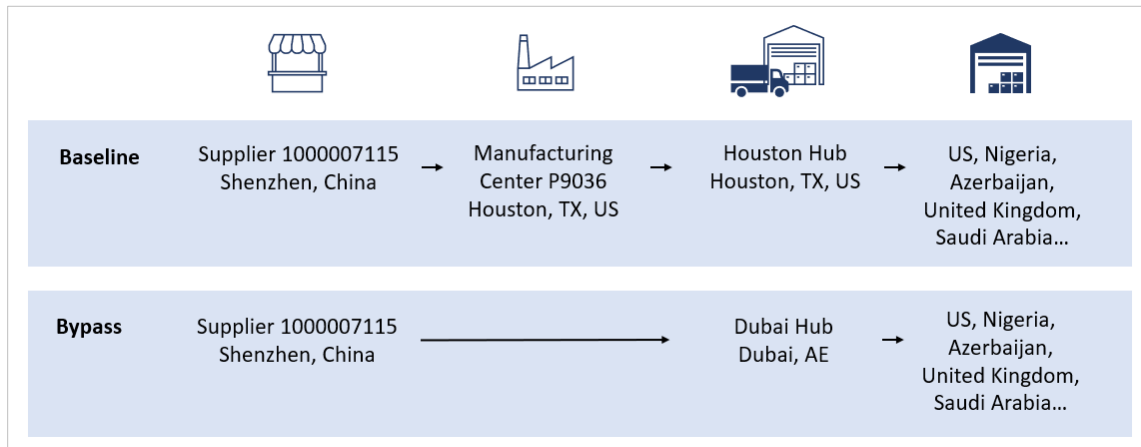
Figure 5

Example of Cost Savings: Part S-400251

We also calculated the savings in the bypass scenario with higher demand. The results were similar to the scenario with baseline demand. The detailed demand assumptions and the results are presented in Appendix B.

4.2   Sensitivity Analysis: Distribution Cost vs. Emissions Cost

We conducted a sensitivity analysis to investigate the impact of assigning more importance to the distribution cost or to the emissions cost in the objective function.

Let λ be a real number between 0 and 1 such that the total cost Z is given by:

$$Z = \lambda \left(Z_{TC} + Z_{DC} \right) + \left(1 - \lambda \right) Z_{GHGC} \tag{29}$$

As previously defined, Z_{TC} is the transportation cost, Z_{DC} is the duties cost, and Z_{GHGC} is the emissions cost. For λ = 1, all the weight is assigned to the distribution cost $(Z_{TC} + Z_{DC})$. In this case, the model ignores the emissions cost. On the other end of the spectrum, for λ = 0, all the weight is assigned to the emissions cost Z_{GHGC}. In this case, the model ignores the distribution cost. We ran the model for different values of λ ranging from 0 to 1 and plotted the results in Figure 6.

Figure 6

Sensitivity Analysis: Distribution Cost vs. Emissions Cost

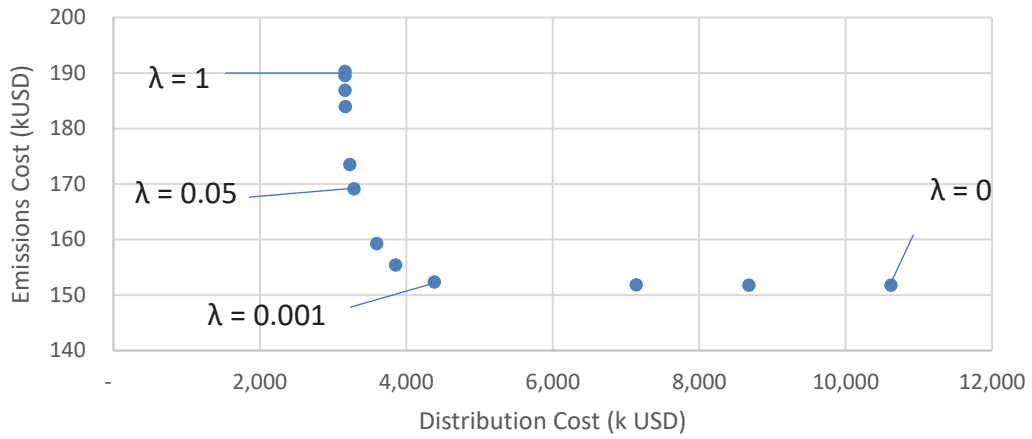Table 9 displays the distribution costs and emissions for different values of λ, along with their respective variations when compared to a baseline where only distribution costs are considered (λ = 1).

Table 9

Sensitivity Analysis: Distribution Cost vs. Emissions

| λ	Distribution Cost (k USD)	Emissions (tonne CO_2e)	Distribution Cost Variation vs. λ = 1	Emissions Variation vs. λ = 1
1.00	3,162	1,815	-	-
0.75	3,163	1,807	0.0%	-0.4%
0.50	3,164	1,782	0.1%	-1.8%
0.25	3,170	1,754	0.2%	-3.3%
0.10	3,230	1,654	2.1%	-8.8%
0.05	3,287	1,613	3.9%	-11.1%
0.02	3,595	1,519	13.7%	-16.3%
0.01	3,853	1,482	21.8%	-18.3%
0.001	4,386	1,453	38.7%	-19.9%
0.0001	7,143	1,448	125.9%	-20.2%
0.00001	8,678	1,447	174.4%	-20.3%
0	10,621	1,447	235.8%	-20.3%

Figure 6 and Table 9 show that decreasing λ from 1 to 0.05 results in a decrease in emissions costs while distribution costs remain mostly stable. However, as λ decreases from 0.001 to 0, emissions costs remain relatively constant while distribution costs experience a significant increase.

4.3   Sensitivity Analysis: Maximum Allowed Lead Time

We also conducted a sensitivity analysis to investigate the impact of reducing the maximum allowed lead time. We first varied the maximum allowed lead time for Buy-To-Order parts (T_{BTO}) by decrements of one day while keeping the maximum allowed lead time for Buy-To-Stock parts (T_{BTS}) constant. Then we varied T_{BTS} while keeping T_{BTO} constant. The results are shown in Figure 7 and Figure 8, respectively.
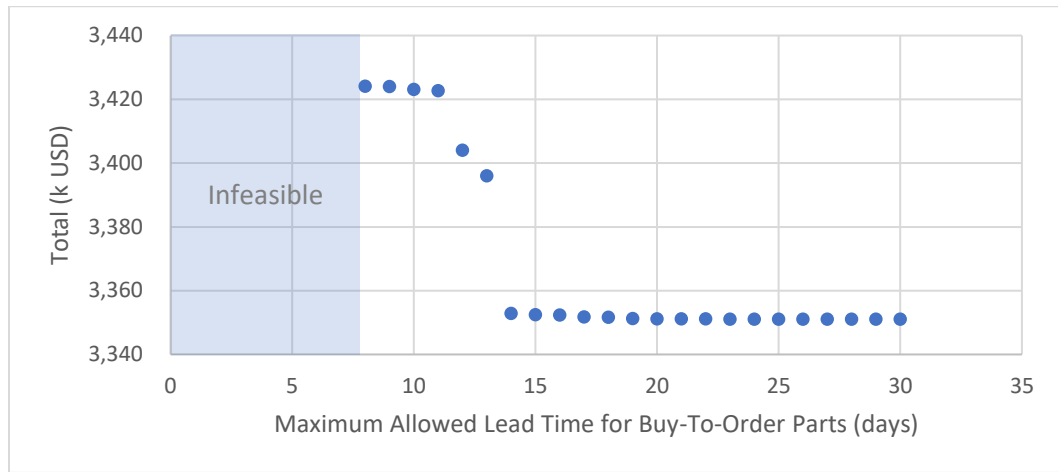
Figure 7

Sensitivity Analysis to Changes in Maximum Allowed Lead Time for Buy-To-Stock Parts
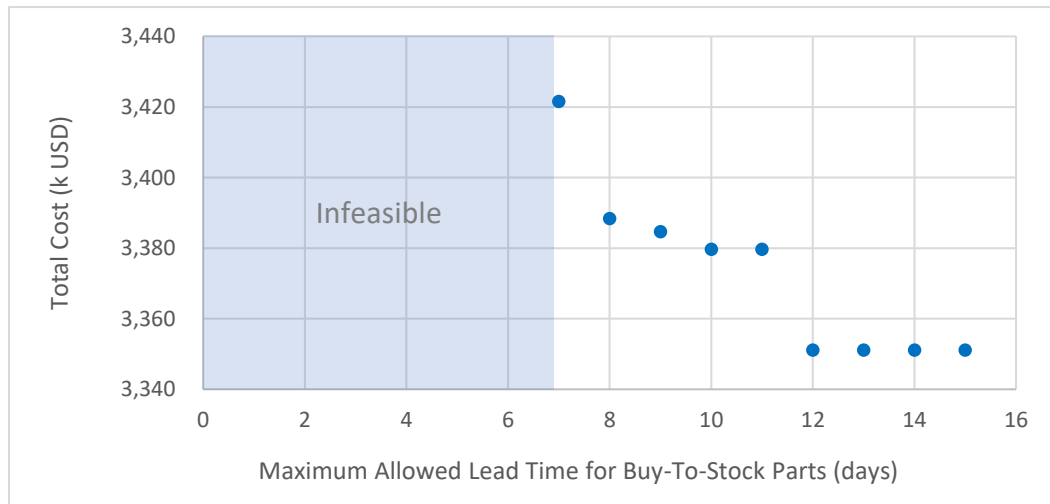
Figure 8

Sensitivity Analysis to Changes in Maximum Allowed Lead Time for Buy-To-Order Parts

From Figure 7, we observe that the total cost remains constant when reducing the maximum allowed lead time for Buy-To-Stock parts from 15 to 12 days. By further reducing this maximum allowed lead time, we observe two increases in the total cost, one at 11 days and the other at seven days. For less than seven days, the model does not provide any feasible solution.

Similarly, Figure 8 shows that the total cost remains constant when reducing the maximum allowed lead time from 30 to 14 days. The main increases in the total costs occur at 13 days and 11 days. After eight days, the model does not offer any feasible solution.

5. DISCUSSION

In this section, we discuss the results presented in Section 4: the savings generated by bypassing the manufacturing centers, the trade-offs between the distribution cost and emissions, and the sensitivity analysis with respect to lead time. We conclude with the limitations of our study.

5.1 Bypassing the Manufacturing Centers

We showed in Section 4.1 that bypassing the manufacturing centers results in a 3.7% reduction in distribution costs and a 1.7% reduction in GHG emissions. The findings reveal two main insights. First, most of the reduction in distribution cost is attributed to the reduction in duties. The example of part S-400521 (shown in Figures 4 and 5) illustrates this phenomenon. Second, 10 parts account for 92.4% of the overall savings, as shown in Table 8. This is good news for the sponsor company: it can implement the changes (such as updating its purchasing master data) for these top parts in a short amount of time and generate immediate savings.

It is worth noting that bypassing the manufacturing centers generates benefits that extend beyond the transportation and duties costs. Indeed, our model did not consider the inbound and outbound handling of the parts in the manufacturing centers. The handling cost is part of the fixed cost of operating the manufacturing centers. Bypassing the manufacturing centers would reduce the time spent in receiving, putting away, picking, packing, and loading the parts, as well as the administrative work to pay the logistics providers. Whether these reductions would translate into hard savings cannot be guaranteed, but at a minimum, they would allow the manufacturing centers' logistics team to reallocate the time saved to activities that improve their operations.

5.2 Trade-offs Between Distribution Cost and Emissions

We can derive several insights from the sensitivity analysis that we conducted by varying the weight assigned to distribution cost and emissions cost. Table 9 shows that, by starting at $\lambda = 1$, i.e., assigning all the weight to the distribution cost, and then decreasing the value of λ to 0.1, i.e., assigning a

90% weight to the emissions cost, the distribution cost only increases by 2.2%. This means that the model is driven primarily by the distribution cost. Indeed, we would need to assign to the GHG emissions 10 times more weight than to the distribution cost before the model starts to noticeably disadvantage the latter. This is explained by the fact that the cost of emissions is very small compared to the cost of distribution due to the current GHG emissions pricing.

Another insight derived from the sensitivity analysis is that the company can achieve moderate but quick wins regarding GHG emissions reduction. Indeed, Table 9 shows that by adopting a transportation plan that increases distribution costs by only 0.2%[2] (λ = 0.25), the company can achieve a 3.3% reduction in GHG emissions. However, beyond a 38.7% increase in distribution cost (λ = 0.001), the GHG emissions remains quasi-flat.

Finally, our results show that, at best, the company can reduce its emissions in the network by 20.3% (λ = 0). This number may seem low considering the corresponding 236% increase in distribution cost that it requires, but it makes sense considering the design of the distribution network. Indeed, the network for the distribution of M&S uses four modes of transport: air freight, express courier, FTL and LTL. The first two modes have an emissions intensity factor of 0.920 kg CO_2e / t.km, while FTL and LTL have intensity factors of 0.093 and 0.140 kg CO_2e / t.km, respectively. To substantially reduce emissions, the transportation plan would need to switch from air freight and express courier to FTL and LTL. However, only a small proportion of transportation lanes have all four modes available. Most of the international lanes have only air freight and express courier options for geographical reasons, so the opportunities for switching to less carbon intensive modes are rare.

In conclusion, there are no acceptable increases in distribution cost that can achieve reductions in emissions capable of substantially contribute to the company's stated goal of 30% reduction in Scope 3

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[2] Compared to the optimal solution obtained by considering only the distribution cost.

emissions. Reducing GHG emissions beyond 20.3% would require additional measures. Perhaps the most effective one would be switching from air to ocean and from truck to rail. However, ocean and rail shipping have long lead times. Further analysis that considers inventory planning decisions would need to be conducted. Another possible measure would be to allow direct shipments from the suppliers to the field warehouses.

5.3   Sensitivity Analysis: Maximum Allowed Lead Time

From our analysis showing the effect of tightening the lead time constraint for Buy-To-Stock parts (presented in Figure 7), we observe that the total cost remains constant when reducing the maximum allowed lead time for Buy-To-Stock parts from 15 to 12 days. By further reducing this maximum allowed lead time, we observe two increases in the total cost, one at 11 days and the other at seven days, that result in a cumulated total cost increase of 0.9% and 2.1%, respectively. These jumps are caused by a switch to faster modes to meet the more stringent lead time constraints. After seven days, the model does not provide any feasible solution, as the maximum lead time allowed is higher than the lead time from the DCs to some destinations, even with the fastest mode (i.e., express courier).

Similarly, Figure 8 shows that the total cost remains constant when reducing the maximum allowed lead time from 30 to 14 days. The main increases in the total costs occur at 13 days and 11 days, resulting in a cumulated total cost increase of 1.3% and 2.1%, respectively. Again, these jumps are caused by a switch to faster modes of transport to satisfy the more stringent lead time constraints. After eight days, the model does not offer any feasible solution, as the maximum lead time allowed is higher than the combined minimum lead times from the suppliers or from the manufacturing center to the DCs, and from the DCs to some destinations.

These findings suggest that the company has the opportunity to decrease the maximum allowed lead times without incurring additional costs. Additionally, it is possible to significantly reduce the maximum allowed lead time while only incurring a 2.1% increase in distribution costs. However, to assess

all the financial implications of this course of action, a more detailed investigation of its impact on inventory levels is necessary.

5.4   Limitations

Our model and analysis come with limitations that provide directions to the company for future studies. The first set of limitations is related to the simplifying assumptions we took when building our model. First, we assumed that the flows were conserved in manufacturing centers and DCs, which is not the case since these nodes hold inventory. Second, we assumed that the demand is deterministic, whereas demand can vary according to the tenders won by the company and to the drilling season in some areas of the world. Third, we adopted a simplified duties calculation method that only considers the departure country; however, duties depend on the Harmonized Tariff System code of the parts imported and the country of origin of those parts. Duties are especially important in light of our finding that they account for most of the savings in the bypass scenario, hence the importance of augmenting the mathematical formulation to model duties more accurately. Lastly, we calculated the transportation cost based on average shipment sizes and we assumed those shipment sizes to be constant.

Another set of limitations pertains to the data completeness and quality. We imputed values for missing data with the best possible approximation, particularly for shipment sizes from suppliers to the manufacturing center, supplier locations, transportation rates not included in the negotiated rates, and lead times for express courier. We also used maximum and minimum values for outliers for the weight of parts and transportation costs.

Beyond addressing the issue of incomplete data, future projects could consider the effect of holding inventory in manufacturing centers and in DCs. This could be achieved by extending the MILP model (1)-(28) to consider for multiple decision periods. Another possible focus for future analysis could be considering stochastic demand and a finer granularity in the calculation of duties.

6. CONCLUSION

Our project had three objectives. First, providing an optimal transportation plan for M&S through the network of suppliers, manufacturing centers, DCs, and field warehouses, considering both distribution and GHG emission costs. The second objective was estimating the reductions that the company could achieve in terms of distribution cost and emissions by bypassing the manufacturing centers for eligible parts. Finally, our project aimed at providing an understanding of the trade-offs between distribution cost, emissions, and lead time.

To achieve these objectives, we built a MILP model that minimizes the distribution costs (transportation and duties) and GHG emissions cost under demand and maximum lead time constraints. Our model provides an optimal transportation plan in terms of the quantity and mode of transport throughout each echelon of the network for each part in scope.

Our results show that bypassing manufacturing centers reduces distribution cost by 3.7% and GHG emissions by 1.7%. While the reductions appear modest, they represent a quick win for the company, especially considering that most of the savings are generated by a small number of parts.

Furthermore, by varying the weight assigned to the distribution cost and to the emissions cost, we analyzed the trade-offs between the distribution cost and the emissions. First, we found that the optimal transportation plan is primarily driven by distribution costs due to the low emission prices. Second, by shifting the weight assigned to emissions in the objective function (75% for emissions vs. 25% for distribution cost), the company can reduce its emission by 3.3% while increasing the distribution cost by only 0.2%. Finally, by optimizing only the GHG emissions, the maximum that could be achieved is a 20.3% reduction in emissions, but it comes in exchange for a very high distribution cost. Higher reductions can be possible by introducing lower emissions mode of transport alternatives, such as rail and ocean. This solution, however, would need to analyze the impact on inventory. Another alternative is to study the effects of direct shipments from suppliers to field warehouses.

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APPENDIX A: Additional data-related assumptions

Assumptions on transportation rates:

- The transportation rates assume non-dangerous goods, without considering detention and expediting charges.

- The air freight rates include the average pre-carriage cost.

Assumptions on duties:

- A simplified, country-level duty rate is used regardless of the Harmonized Tariff System code that applies to the part:

  o Suppliers to manufacturing center P9036 (US) or to Houston Hub

    ▪ China to the United States: 20%

    ▪ Mexico and Canada to the United States: 0%

    ▪ Rest of the world to the United States: 5%

  o Suppliers to Dubai Hub, manufacturing center P9036 (US) to Dubai Hub, and Houston Hub to Dubai Hub: 0% (Dubai Hub is in the Free Trade Zone)

  o Houston Hub and Dubai Hub to the rest of the world: 5%

Assumptions on lead time:

- The lead time for air freight includes the processing time, the transit time, the export clearance lead time, the fumigation lead time, the FTL-pre-carriage lead time, and the maximum time until the next departure (worst case scenario assuming that the departure was just missed)

- The lead time for express courier shipments uses the following simplifying assumptions:

  o United States/Canada to United States/Canada: 2 days

  o United States/Canada to Europe and Europe to United States/Canada: 5 days

  o Everything else: 7 days

APPENDIX B: Bypass Scenario with Higher Demand

Demand assumptions for 2023 (compared to 2022 demand):

- Middle East region: +22%

- North America region: +18%

- Rest of the world: +10%

Table B1

Savings for the Bypass Scenario with Higher Demand

	Baseline	Bypass	Savings	Relative Savings
Distribution Cost	3,735	3,599	136	3.6%
Transportation Cost	1,594	1,573	21	1.3%
Duties Cost	2,141	2,026	115	5.4%
Emission Cost	216	213	4	1.7%
Total Cost	3,952	3,812	140	3.5%
Emissions (tonne CO2e)	2,063	2,028	35	1.7%

Note. Costs in thousands of US dollars per year