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Synchromodal Supply Chains for Fast-Moving Consumer Goods

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Featured Application: Supply Chain Management.

Abstract: Synchromodality is an emerging concept in supply chain management. A synchromodal supply chain can be defined as a multimodal transportation planning system, wherein the different agents work in an integrated and flexible way that enables them to dynamically adapt the transport mode based on real-time information from stakeholders, customers, and the logistic network. The potential of synchromodality for the fast-moving consumer goods (FMCG) industry is related to the nature of business. The FMCG market is characterized by relatively low margins and high turnover, which is especially important in export supply chains. However, for a company, it may be challenging to objectively evaluate the costs and benefits, not to mention the design of a synchronized supply chain. In order to facilitate the adoption of the concept and guide the practitioners, our study put forward the following research questions: What should be considered in incorporating synchromodality in the export supply chain for FMCG? How should companies approach tradeoffs among factors affecting the supply chain? To answer these questions, we propose an adaptable framework, which should be considered a primary contribution of our study. The framework incorporates the center of gravity model, mixed integer linear programming, and sensitivity analysis. The framework is validated using a real-world problem from a multinational FMCG company. The problem involves the optimal volume allocation and the selection of the most efficient transportation mode for inland freight. Our study demonstrates that incorporating synchromodality in the export supply chain could reduce the overall cost by 9% and enhance flexibility by allowing multiple modes of transportation.

Keywords: synchromodality; supply chain; consumer goods; optimization

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1. Introduction

Supply chains are the blood vessels of the global economy. From large retailers to semiconductor manufacturers, business leaders worldwide use their supply chain as a strategic weapon to achieve competitive advantage and maintain business continuity. Supply chains constitute complex systems defined by the suppliers, plants, warehouses, and the corresponding material flows. A substantial share of the total supply chain cost is associated with the location of the facilities and the determination of optimal product flows between them [1]. In order to remain competitive, contemporary supply chains leverage the efficiency and effectiveness of their logistics network. That is why network design and flow synchronization are critical factors in the success of any supply chain [2]. Synchronization is a common concept in various scientific disciplines, such as physics, biology, and chemistry [3]. In a broader sense, synchronization means aligning a certain behavior or state over time. For example, according to Osipov et al., "synchronization is the capacity of objects of different nature to form a common operation regime due to interaction or forcing" [4]. This mechanistic definition is well-aligned with the idea of supply chain synchronization, which can be viewed as a process of matching supply with demand through the coordination of material, financial, and information flows across multiple stages [5]. As a result, a synchronized supply chain is akin to a mechanism full of gears and cogs that operate in harmony.

The importance of synchronized supply chains is especially notable in the context of maritime freight and ocean export. Since the containerization revolution of the 1970s, maritime transport has been vital for international trade [6]. Nowadays, it represents 80% of global trade by volume and 70% by value. In 2020 alone, 10.7 billion tons of shipped goods were seaborne, which is equivalent to 815.6 million twenty-foot equivalent units [7]. However, the COVID-19 pandemic disrupted supply chains, leading to canceled sailing, port delays, and container shortages. The pandemic also generated changes in demand that led to increased volatility, contributing to significant delays [8]. The trade contraction, in its turn, forced container shipping firms to cancel scheduled sailings and consolidate shipping routes to focus service on major ports. As trade recovered in the second half of 2020, the container firms struggled to restore capacity to previous levels. The distributed system was not prepared for the rapid recovery in demand, and firms had trouble getting products to customers. As a result, vessels had to operate close to maximum capacity, which depleted shipping container inventory at major ports [9]. The substantial imbalance between the demand and supply resulted in an unprecedented growth in the price of container rates and maritime freight costs [9]. To be more specific, the global schedule reliability dropped from 75% in 2020 to 35% in 2021, and ocean freight rates increased by 800% compared to pre-pandemic [10]. Newton's first law states that every object will remain at rest unless compelled to change its state by the action of an external force. Disruptions and "black swan" events are the strongest drivers of innovation. The ocean export supply chains experienced unprecedented shock, which increased awareness of synchromodality among scholars and industry practitioners.

Synchromodality is an emerging concept in supply chain management, developed and established in the Benelux region during the last decade [11]. The seminal study defined the synchromodal supply chain as "a multimodal transportation planning system, wherein the different agents involved in the supply chain work in an integrated and flexible way that enables them to dynamically adapt the transport mode they use based on real-time information from stakeholders, customers, and the logistic network" [2]. According to Giusti et al., the primary purpose of synchromodality is to reduce costs, emissions, and delivery times while maintaining the quality of supply chain service through efficient utilization of available resources and synchronization of transport flows [11]. At this point it is essential to highlight that the adopted definition is not arbitrary and further justified in the literature review section.

Intuitively, synchromodality benefits companies, especially in the fast-moving consumer goods (FMCG) industry. The potential of synchromodality for FMCG companies is related to the nature of business. FMCG are the products that customers buy on a regular basis, including blades and razors, fabric and home care, hair care, health care, oral care, baby care, personal care, and skin care. The FMCG market is characterized by a wide variety of consumers, potentially volatile demand, and low consumer loyalty [12]. FMCG have relatively low costs and high turnover. So, while the margin of an individual product is usually relatively small, the total net profits can be significant because of quantities and scale [13]. In this context, objectively evaluating the tradeoffs between costs and benefits and the design of a synchronized supply chain might be challenging. In this regard, we postulate the following research questions: (1) What should be considered in incorporating synchromodality in the ocean export supply chain for fast-moving consumer goods? (2) How should companies approach tradeoffs among factors affecting supply chains?

In order to answer the postulated research questions, we propose an adaptable framework for synchronized supply chain design. The framework was initially developed as part of the capstone research conducted at the MIT Center for Transportation and Logistics in collaboration with a multinational FMCG company [14,15]. The framework incorporates the center of gravity model, mixed integer linear programming (MILP), and sensitivity analysis. The center of gravity analysis is applied to provide a recommendation for the mixing center location and confirm if the current location is suitable for the business. The MILP model is used to allocate freight volume. The MILP model incorporates synchromodality by providing the mode switch mechanism and is implemented such that the optimality of the transportation mode depends not only on the transportation cost but also considers the inventory holding cost with regard to lead time and the expected service level. In light of the scarcity of company resources, a sensitivity analysis is performed to help decision-makers prioritize their investments for the most notable supply chain network improvement.

The remainder of this paper is organized as follows. Section 2 presents the literature review that justifies the definition of synchromodality, classifies related work, and highlights the research gap. Section 3 presents the problem that the multinational FMCG company encountered. Section 4 introduces the methodology at a high level and provides the rationale behind the choice of the individual components. Section 5 presents the solution to the problem under consideration using the proposed methodology. Section 6 highlights the advantages of the proposed framework and explains how it can be generalized and applied to similar problems within the domain. This section also shares the insights and managerial implications and discusses the impacts of the solution on sustainability. Lastly, Section 7 summarizes the paper and suggests promising directions for future research.

2. Literature Review

Even though the previously conducted literature reviews on synchromodality show that the vast majority of the studies are predominantly theoretical, exploratory, and qualitative [2,11,16], our study attempts to pay attention to both theoretical and practical contributions. Theoretical works have been analyzed to define the concept of synchromodality and understand the potential value it can bring. The practical works are studied in order to adopt best practices, find the research gaps, and highlight the novelty of our contribution.

2.1. Concept of Synchromodality

Synchromodality addresses a pivotal aspect in the transportation research debate: identifying the most efficient and effective combination of transport modes [16]. Even though synchromodality is the most recent modal shift paradigm, it is essential to point out that there is a plethora of legacy logistics paradigms implying the use of modal shifts, including multimodality, intermodality, combined modality, and comodality [17]. These paradigms can be defined as follows:

- Multimodality is the transportation of goods by a sequence of at least two different transport modes [17];
- Intermodality is the transportation of goods integrating at least two modes such that the load is transported door to door using the same load unit [18];
- Combined modality is a sustainable form of intermodal transportation [19];
- Comodality is efficient transportation through optimal and sustainable use of resources [20].

A recent study summarized the difference between synchromodality and legacy modal shift paradigms, which allows us to view synchromodality as the outcome of the evolution of modal shift paradigms [2]. Initially focused on improving the efficiency of the transport system, these paradigms have gradually evolved and come to incorporate multiple objectives to optimize the tradeoff between efficiency, service levels, and sustainability [11]. Table 1 highlights these differences with regard to such capabilities as integration, sustainability, efficiency, and flexibility.

Table 1. Comparison between synchromodality and legacy modal shift paradigms based on such core capabilities as integration, sustainability, efficiency, and flexibility. Adapted from [2].

Concept	Two or More Modes of Transportation	Integration	Sustainability	Efficiency	Flexibility
Multimodality	X				
Intermodality	X	X			
Combined	X	X	X		
Comodality	X	X	X	X	
Synchromodality	X	X	X	X	X

Integration is the process of connecting decisions and actions across an end-to-end supply chain to drive total value for all stakeholders. This process involves strategy alignment, effective management of operations, and maintaining reciprocal flows of information among stakeholders [21]. The definition of integration in the context of synchromodality and multimodal transportation can be narrowed down to the process of connecting different modes of transport to create a single, seamless transportation system. Integration of the modes of transportation can also involve the real-time coordination of schedules and other logistical factors [22]. Synchromodality is also closely associated with the concept of flexibility, which refers to the ability of a transportation network to shift modes and routes to accommodate changes in demand or unexpected events. The flexibility in a broader sense can also include the ability to adjust the number and type of vehicles. Efficiency refers to the ability of the supply chain network to minimize delays, reduce costs, and increase service levels. Efficiency can also be viewed in light of the efficient utilization of resources under various constraints and tradeoffs [23]. For example, synchromodal solutions are especially sensitive to the tradeoff between transportation and inventory holding costs because as companies ship more frequently or use faster modes with smaller maximum capacity, transportation costs tend to increase, but inventory costs decrease. However, if the priority is given to slower modes that can carry larger order quantities, the transportation costs decrease, but inventory costs increase due to the increase in cycle stock. Additionally, safety stock also becomes larger due to the longer lead times and increased lead time variability [24].

Sustainability, in general, refers to the ability to meet the needs and aspirations of the present generation without compromising the resources needed for future generations to meet their needs [25]. In the context of synchromodality, sustainability refers to the ability to maintain or improve the overall environmental impact of a supply chain without undermining its efficiency [26]. At first glance, it may sound counterintuitive, but in many cases, there is a congruence between environmental costs and financial costs related to transportation and logistics. For example, faster modes of transport (such as trucks) use more fuel and have much larger carbon footprints compared to slower modes of transport (such as ships and railways) [27]. Additionally, capacity underutilization also consumes large amounts of fuel. As a result, both shippers and carriers, as well as the environment, bear the costs of underutilized capacity. Synchromodality allows the switch from trucks to rail and better capacity utilization through flow consolidation. As a result, the company can notably reduce its carbon footprint and enhance sustainability.

The view of synchromodal supply chains through these critical capabilities involves considering the economic and environmental performance of the system as well as its ability to adapt to changing needs, markets, and technologies. It emphasizes the importance of creating a resilient, low-carbon transportation system that is ecologically sound and economically viable while meeting stakeholders' needs.

Synchromodality is an emerging and multifaceted concept. Since the concept covers different and sometimes conflicting capabilities such as integration, sustainability, efficiency, and flexibility, there is a slight disagreement and inconsistency among authors in the definition of the concept as well as in the advantages and potential value that the adoption can bring [16]. Table 2 summarizes the advantages and value of synchromodality emphasized by different authors.

Table 2. Advantages of synchromodality and potential value it can bring.

Advantages and Value of Synchromodality	Reference
A flexible, efficient, and sustainable transportation strategy	[28]
An efficient, sustainable, and reliable transportation network	[29]
Alternatives and options for flexibility and responsiveness	[30]
Real-time design and coordination of value chains in the transportation system	[31]
Flexibility in changing different modes, emission reduction	[32]
Efficient transportation service based on real-time information	[17]
Cost and emission reduction without sacrificing the service level	[33]
Efficient, reliable, flexible, and sustainable services	[11]
Dynamic mode adaptation based on real-time information	[2]
Carbon footprint reduction and increased efficiency	[34]

Given these facts, our study adopts the most pervasive definition of synchromodality by Acero et al., which encompasses all the critical capabilities and highlights the value that the adoption of the concept can bring: "a multimodal transportation planning system, wherein the different agents involved in the supply chain work in an integrated and flexible way that enables them to dynamically adapt the transport mode they use based on real-time information from stakeholders, customers, and the logistic network" [2].

2.2. Strategic Tradeoffs in a Synchromodal Supply Chain

Even though synchromodality is an emerging concept, several research projects have already demonstrated how supply chain objectives can be achieved by avoiding empty capacity, reacting to disruptions, and reducing transportation by trucks in favor of slower modes [11]. For example, Van Riessen et al. studied the effects of disturbances on the operational planning of container transportation in a synchromodal network. The developed linear model optimizes the transportation flow and involves container consolidation. Additionally, the authors proposed to measure the severity of a disturbance as the additional cost incurred by updated planning [35]. Rivera and Mes presented an approximate dynamic programming model for selecting freights in intermodal long-haul round trips. The approach was tested based on data from a Dutch logistic service provider [36]. Li et al. proposed a model based on a predictive flow control approach. In this study, the authors aimed to model cooperation among stakeholders, which is important within the framework of synchromodality. The model considered flow optimization as well as consolidation in multiple interconnected subnetworks [37]. Zhao et al. studied the location of consolidation centers in China to improve the internal and China–Europe rail transport efficiency. First, the authors established criteria to preselect some candidates and used the information about railways, highways, and national roads to build a graph-based model. Then, they used a K-shell method to evaluate the importance of each node and a MILP model to find the best location [38]. Dong et al. proposed parallel optimization between transport and storage, highlighting the importance of considering the synchronization of operations across different levels. The authors used a case study to show how the proposed approach could increase the utilization of rail transport, resulting in a reduction of emissions and total cost savings. The total cost equation included transportation and inventory but did not consider the cost associated with facilities' operations [16]. Qu et al. developed a MILP model to plan hinterland freight transportation. The model allowed mode switch from truck to barge and could improve coordination by rescheduling the shipment flows [39]. In a recently published study, Guo et al. considered a global synchromodal transport network. The authors proposed a hybrid stochastic approach to match shipments. The performance of the developed approach was evaluated in a numeric experiment with synthetic data [40].

Synchromodality requires treating supply chains in an integrated and flexible way. Therefore, it is crucial for a framework and the underlying model to incorporate strategic decisions that affect total cost and supply chain performance. Table 3 classifies the related work based on the strategic decisions allowed by a model.

Table 3. Related work with regard to strategic decisions.

Reference	Mode Switch	Flow Optimization	Consolidation	Facility Location
[35]	X	X	X	
[36]	X	X	X	
[37]	X	X		
[38]	X	X	X	X
[16]	X	X	X	
[39]	X	X		
[40]	X	X	X	

Additionally, in order to facilitate the holistic approach to supply chain design, the objective function of the optimization model should incorporate transportation, inventory holding, and facility operating costs in the total cost equation. For example, it is crucial to consider both transportation and inventory holding costs and the tradeoff between them [24,41]. Namely, as companies ship more frequently or use faster modes with smaller capacity, transportation costs tend to increase, but inventory costs decrease. However, if the priority is given to slower modes that can carry larger order quantities, the transportation costs decrease, but inventory costs increase due to the increase in cycle stock. Safety stock also becomes larger due to the longer lead times and increased lead time variability. Table 4 classifies the related work based on the cost structure in the total cost equation. The table illustrates that most studies are focused exclusively on transportation and do not take inventory and facilities into account.

Table 4. Related work with regard to cost structure.

Reference	Transportation	Inventory	Facility Operation
[35]	X		
[36]	X		
[37]	X		
[38]	X		X
[16]	X	X	
[39]	X		
[40]	X		

Summarizing, our contribution closes the research gap by incorporating such critical strategic transportation network design decisions as mode switch, facility location, and flow optimization into the MILP model and associated framework. Additionally, the proposed model approaches the total cost equation holistically, paying specific attention to the tradeoff between transportation and inventory and considering facility operation cost. It is also worth mentioning that our framework and the underlying model are tested on real data provided by one of the largest FMCG companies in the world.

3. Problem under Consideration

The FMCG company under consideration deals with 12 categories of products manufactured by 13 plants in North America. These finished products are sent in domestic pallets to a mixing center for consolidation. The mixing center performs three main activities: loading and unloading of trailers, case picking, and pallet exchange from domestic pallets to export pallets. The mixing center manages approximately 7000 export containers annually and sends them to 164 customers in 37 Latin American countries via 7 carriers. The resulting supply chain is highly complex, with significant volume and multiple touchpoints. Moreover, the North American supply chain is designed and optimized for domestic shipments, not for export shipments, which creates opportunities to optimize the end-to-end process for these export shipments to offset the rising global commodity costs, considering the company's existing domestic supply chain.

Figure 1 illustrates the current supply chain design. The material flow from the supply warehouses to the customers' ports of discharge is subject to optimization. The location of the mixing center of the FMCG company has crucial relevance, given that this will determine the inland costs between the supply warehouse and the mixing center and the freight transportation from the mixing center to the corresponding port of loading. There are 13 supply warehouses, and they are located in the center and on the east coast of the United States. Our study aims to confirm if the current mixing center location is optimal or propose a new location based on the optimization model. There are 6 ports of loading on the east coast of the country and 41 ports of discharge located in 37 countries in Latin America.

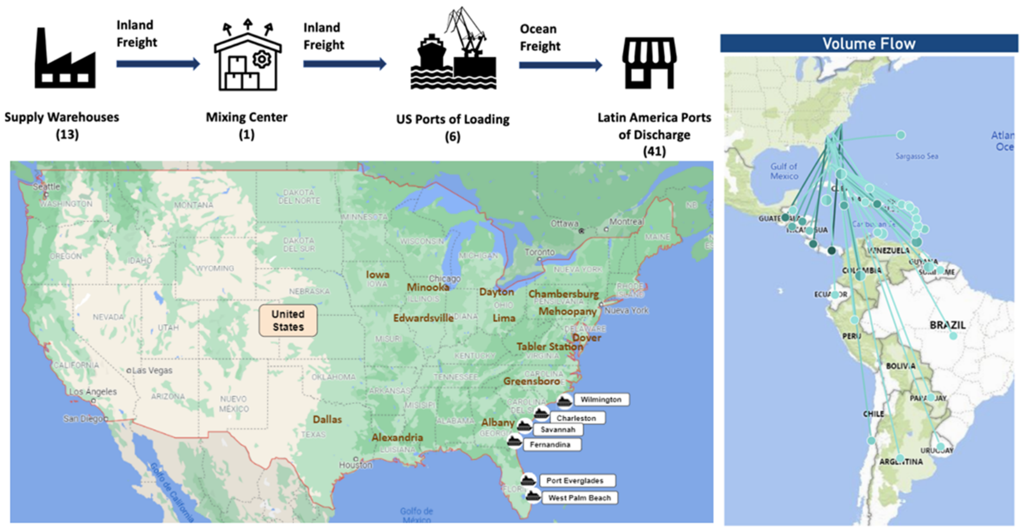


Figure 1. Current supply chain network, ports' location, and current flow allocation from the US ports to Latin American customers.

The total cost of the supply chain incorporates transportation, inventory holding, labor, warehouse, and stock-out costs. Transportation and inventory holding costs are composite. The transportation cost includes a combination of different charges related to port expenses, custom process, administrative fees for customs clearance and technical control, customs broker fees, terminal handling charges, freight pick-up, freight transport, export charges, import charges, fuel, and hedging against risk. The inventory holding cost, in its turn, includes expenses related to storing or holding the products, warehousing, labor, insurance, and rent.

Besides costs, lead times and service levels are important factors to consider. Lead time refers to the time between a process's initiation and finish [42]. Failure to replenish stock is mostly caused by lead time delays, undermining inventory management and customer satisfaction. According to Sharman, extended lead times can end up costing the organization money, and there is a risk of running out of inventory or using unreliable suppliers [43]. Speed to market is important for companies in a context where competitors might introduce new products quicker and take market share. The straightforward ways to reduce the lead time include an increase in order frequency and supply consolidation. The service level can be defined as the probability that there will not be a stock-out within a replenishment cycle [24].

Companies naturally try to satisfy as many customers as possible to maximize their sales and revenue. However, in light of the cashflow scarcity, the service level creates a tradeoff between the cost of inventory and the cost of stock-out [24]. In most sectors, targeting high service levels is the norm because this is one of the key factors in strengthening customer loyalty. However, maintaining high inventory levels is costly and risky, given that products are expensive to buy or produce, they need space to be stored, they expire, and become obsolete. In addition to costs, lead times, and service levels, the sustainability and flexibility aspects are essential to consider. The synchromodality naturally improves flexibility by allowing the mode switch from truck to rail, depending on the flows within the network and market conditions. In many cases, there is also a congruence between environmental costs and financial costs related to transportation and logistics. Although emissions vary significantly across different modes of transportation and operating conditions, faster modes of transport (such as trucks) generally use greater amounts of fuel and have much larger carbon footprints compared to slower modes of transport (such as ships and railways) [27]. Our study sees this fact as a "low-hanging fruit". Synchromodality allows the switch from trucks to rail and better container utilization through flow consolidation. As a result, the FMCG company has the potential to reduce its carbon footprint and improve sustainability, saving money simultaneously.

4. Methodology

The conducted literature review and the problem formulation allow us to set the scope, identify best practices, and select the key variables related to costs, service level, lead time, flexibility, and sustainability. The methodology is very multifaceted. Figure 2 illustrates our methodology as a sequential flow. It visually reflects a summary of the process and the key elements of the resulting framework.

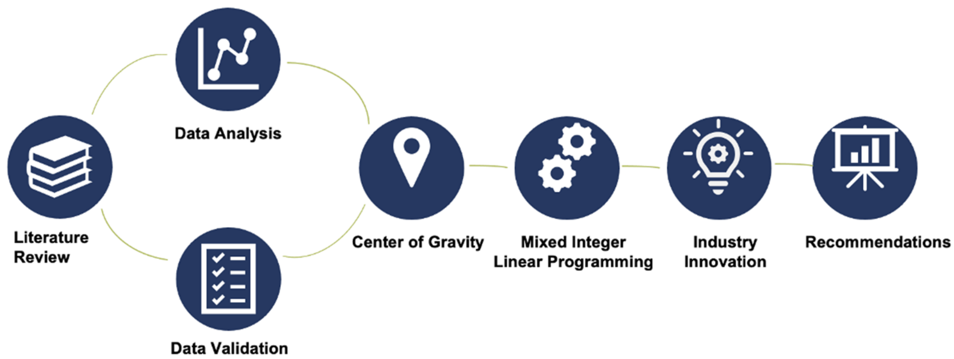


Figure 2. Methodology Flow Chart.

We start with data analysis and validation of the dataset obtained from the FMCG company. Then, a center of gravity analysis is conducted on the existing supply chain to understand whether the current mixing center location is optimal. Next, we take a strategic view of the supply chain network focused on mixing center location and volume allocation strategy using a MILP model. After that, the results are presented to the stakeholders as the innovation that the FMCG company can adopt. Summarizing the quantitative results of the model as well as the inputs from the stakeholders, we finally develop the framework.

4.1. Data Analysis and Validation

We visualize initial data in Power BI to better understand the current volume flow, container distribution by port, volume by port of discharge, and the cost perspective. Power BI is an interactive data visualization software product developed by Microsoft with a primary focus on business intelligence [44]. The visual data analysis helps to ask the company clarifying questions and come up with the next steps according to the available information. Such an analysis is also handy for identifying outliers in terms of ocean freight cost of containers from North America to different ports of discharge in Latin America.

4.2. Center of Gravity

One of the key questions for the FMCG company is to identify the optimal location of the mixing center that is required to send the shipments of different categories to the ports of loading and, ultimately, to the ports of discharge in Latin America. Therefore, the center of gravity analysis is applied to provide a recommendation for the mixing center location and confirm if the current location is suitable for the business. The center of gravity analysis consists of locating the facility considering the existing facilities, the distance between them, and the volume of goods to be shipped between them. It involves expressions to compute the two-dimensional coordinates of the point where the distance between facilities and their expected volume of transportation activity are minimized (Equation (1)).

$$Cx = \frac{\sum dix\ \ Vi}{\sum Vi};\ Cy = \frac{\sum diy\ \ Vi}{\sum Vi}, \tag{1}$$

where C_x is a horizontal axis (longitude) for the new facility location, C_y is a vertical axis (latitude) for the new facility location, d_{ix} is X coordinate of the existing ith location, d_{iy} is Y coordinate of the existing ith location, V_i is volume of goods transported from the ith location [45].

The results of the mixing center's optimal location using center of gravity analysis can be found in the following section.

4.3. MILP Model

The MILP model formulation follows conventions [46–48] and uses interpretable notation. The problem formulation incorporates the elements of the uncapacitated facility location [49], optimal network design [1], and transportation problem [50]. In addition, as our study aims to provide flexibility to the business, the proposed MILP model incorporates the mode switch mechanism between trucks and railroads from the supply warehouses to the mixing center and from the mixing center to the ports of loading. The MILP model is implemented such that the optimality of the transportation mode depends not only on the transportation cost but also considers the inventory holding cost with regard to lead time and the expected service level.

4.3.1. Notation

As the flow synchronization is the key factor in our study, the input variables include: supply by supply warehouse, demand and standard deviation of demand by port of discharge, lead time (via truck, railroad, and ocean), cost of running the mixing center, target service level, review period by port of discharge, and container fill rate by port of discharge. Both demand and supply are measured in containers. Costs are measured in US dollars. The notation employed for formulating the model is described as follows.
Sets:

SWs: set of supply warehouses;
MCs: set of mixing centers;
POLs: set of ports of loading;
PODs: set of ports of discharge.

Parameters:

$tc_{SW,MC}$: truck cost from the supply warehouse to the mixing center;
$rc_{SW,MC}$: rail cost from the supply warehouse to the mixing center;
$tc_{MC,POL}$: truck cost from the mixing center to the port of loading;
$rc_{MC,POL}$: rail cost from the mixing center to the port of loading;
$oc_{POL,POD}$: ocean cost from port of loading to the port of discharge;
opc: operational cost associated with mixing centers;
Ce: holding cost;
D_{POD}: demand at port of discharge;
R_{POD}: review period at port of discharge;

σ_{POD}: standard deviation of demand at port of discharge;
k: safety factor that corresponds to the confidence in the data points within a certain standard deviation value (k = 2.05 based on 98% service level);
L_{POD}: lead time at port of discharge;
$Supply_{SW}$: supply at supply warehouse;
$Open_{MC}$: binary to reflect an open mixing center;
M: an arbitrary large number to ensure the linking constraints.

Decision variables:

$tf_{SW,MC}$: truck flow from the supply warehouse to mixing center;
$tf_{MC,POL}$: truck flow from the mixing center to port of loading;
$rf_{SW,MC}$: rail flow from the supply warehouse to mixing center;
$rf_{MC,POL}$: rail flow from the mixing center to port of loading;
$of_{POL,POD}$: ocean flow from port of loading to the port of discharge;
$RailOpen_{SW,MC}$: binary to reflect an open rail flow from supply warehouse to mixing center;
$TruckOpen_{SW,MC}$: binary to reflect an open truck flow from supply warehouse to mixing center;
$RailOpen_{MC,POL}$: binary to reflect an open rail flow from mixing center to port of loading;
$TruckOpen_{MC,POL}$: binary to reflect an open truck flow from mixing center to port of loading.

4.3.2. Objective Function and Constraints

Equation (2) represents the total cost equation, which is the objective function to minimize. The cost structure is composite and includes the transportation cost (*tc, tf, rc, rf, oc, of*), the cost of running the mixing center (*opc*), and the inventory holding cost (*Ce*). The transportation cost consists of the transportation cost from the supply warehouses to the mixing center and from the mixing center to the port of loading, and the ocean freight cost from the port of loading to the ports of discharge. The inventory holding cost, in its turn, is associated with cycle stock, safety stock, and pipeline inventory.

$$\begin{gathered}\min Z = \sum tc_{SW,MC}\,.tf_{SW,MC} + \sum rc_{SW,MC}\,.rf_{SW,MC} + \sum tc_{MC,POL}\,.tf_{MC,POL} + \\ \sum rc_{MC,POL}\,.rf_{MC,POL} + \sum oc_{POL,POD}\,.of_{POL,POD} + \sum opc.\,Open_{MC} + \\ \sum Ce\left(\frac{D_{POD}\,.\,R_{POD}}{2} + k\,.\sigma_{POD} + D_{POD}.L_{POD}\right)\end{gathered} \tag{2}$$

The objective function has to be minimized subject to constraints represented by Equations (3)–(19).

$$\sum tc_{SW,MC} + rf_{SW,MC} = Supply_{SW}\ ;\ \ \forall\, SW \in SWs \tag{3}$$

$$\sum of_{POL,POD} = Demand_{POD}\ ;\ \ \forall\, POD \in PODs \tag{4}$$

$$\sum tf_{SW,MC} + \sum rf_{SW,MC} = \sum tf_{MC,POL} + \sum rf_{MC,POL}\ ;\ \ \forall\, MC \in MCs \tag{5}$$

$$\sum tf_{MC,POL} + \sum rf_{MC,POL} = \sum of_{POL,POD};\ \ \forall\, POL \in POLs \tag{6}$$

$$\sum Open_{MC} = 1 \tag{7}$$

$$\sum RailOpen_{SW,MC} + \sum TruckOpen_{SW,MC} = 1;\ \ \forall\, SW \in SWs \mid MC\ \in MCs \tag{8}$$

$$\sum RailOpen_{MC,POL} + \sum TruckOpen_{MC,POL} = 1;\ \ \forall\, MC \in MCs \mid POL\ \in POLs \tag{9}$$

$$rf_{SW,MC}\ \le\ RailOpen_{SW,MC}\, M;\ \ \forall\, SW \in SWs \mid MC\ \in MCs \tag{10}$$

$$rf_{MC,POL}\ \le\ RailOpen_{MC,POL} M;\ \ \forall\, MC \in MCs \mid POL\ \in POLs \tag{11}$$

$$tf_{SW,MC}\ \le\ TruckOpen_{SW,MC}\, M;\ \ \forall\, SW \in SWs \mid MC\ \in MCs \tag{12}$$

$$tf_{MC,POL} \leq TruckOpen_{MC,POL}\, M\,;\ \forall\, MC \in MCs \mid POL \in POLs \tag{13}$$

$$tf_{MC,POL}\,, tf_{SW,MC} \geq 0 \text{ and integer };\ \forall\, MC \in MCs \mid SW \in SWs \mid POL \in POLs \tag{14}$$

$$rf_{MC,POL},\ rf_{SW,MC} \geq 0 \text{ and integer};\ \forall\, MC \in MCs \mid SW \in SWs \mid POL \in POLs \tag{15}$$

$$of_{POL,POD} \geq 0 \text{ and integer};\ \forall\, POL \in POLs \mid POD \in PODs \tag{16}$$

$$Open_{MC} = \{0,1\};\ \forall\, MC \in MCs \tag{17}$$

$$RailOpen_{SW,MC}, TruckOpen_{SW,MC} = \{0,1\};\ \forall\, MC \in MCs \mid SW \in SWs \tag{18}$$

$$RailOpen_{MC,POL}, TruckOpen_{MC,POL} = \{0,1\};\ \forall\, MC \in MCs \mid POL \in POLs \tag{19}$$

Equations (3) and (4) balance the problem and prohibit supply over capacity and leave demand unsatisfied. This type of constraint is also known as the consistency condition [50]. Equations (5) and (6) are the nodal flow conservation constraints. These constraints algebraically state that the sum of the flow through arcs directed toward a node equals the sum of the flow through arcs directed away from that node. Equation (7) ensures that only one mixing center is open, which will enforce the consolidation. Since we have incorporated the option of transporting goods by truck or rail from the supply warehouse to the mixing center and from the mixing center to the port of loading, Equations (8) and (9) are necessary to ensure that only one mode of transportation is used for a specific lane. The subscript *Open* refers to an active site or flow between two sites (supply warehouse, mixing center, port of loading, or port of discharge). Equations (10)–(13) link the flow volumes with the facilities. Equations (14)–(19) introduce nonnegativity and domain constraints.

Equation (2) requires a total lead time for pipeline inventory, which is calculated according to Equation (20).

$$\begin{aligned} L_{POD} = {} & \sum RailOpen_{SW,MC}.L_{SW,MC} + \sum TruckOpen_{SW,MC}.L_{SW,MC} \\ & + \sum RailOpen_{MC,POL}.L_{MC,POL} + \sum TruckOpen_{MC,POL}.L_{MC,POL} \\ & + \sum L_{POL,POD}\ \ ;\ \forall\, SW \in SWs \mid MC \in MCs \mid POL \in POLs \end{aligned} \tag{20}$$

4.3.3. Implementation

The MILP model is implemented using Python 3.11 and Gurobi Optimizer, a state-of-the-art solver for mathematical programming [51]. The MILP model outputs the value of a minimal total cost and the optimal solution. The optimal solution consists of integer values that correspond to the container flow allocation between nodes as well as binary values that correspond to the mode choice and the choice of a mixing center for consolidation. The MILP model, a pivotal part of the proposed framework, is tested based on the data provided by the FMCG company. In this regard, it is important to point out that the FMCG company deals with a very mature product, so the network is not subject to changes, demand is quite stable, and the scale of the problem is small with regard to the computational budget. If another company decides to adopt the proposed framework, the inputs should be checked for feasibility, and the problem scale should be taken into account. If the company adopting the proposed framework deals with a significantly larger network, cuts and various heuristics to boost computation performance should be explored.

5. Results

This section starts with the data collection and analysis. We analyzed the available information and performed visualizations in Power BI to obtain a perspective on the current export supply chain of the company. Later, we present the results of the outcome of the center of gravity analysis and the proposal for the grouping of the ports of discharge. After that, we present the mixed integer linear programming model and the sensitivity analysis.

5.1. Data Collection and Analysis

We built visualizations in Power BI to better understand the current volume flow, container distribution by port, volume by port of discharge, and the cost perspective (Figure 3). This data analysis helped to ask the stakeholders clarifying questions and recommend the next steps according to the available information. This analysis was also helpful in identifying outliers in terms of ocean freight cost of containers from North America to different ports of discharge in Latin America.

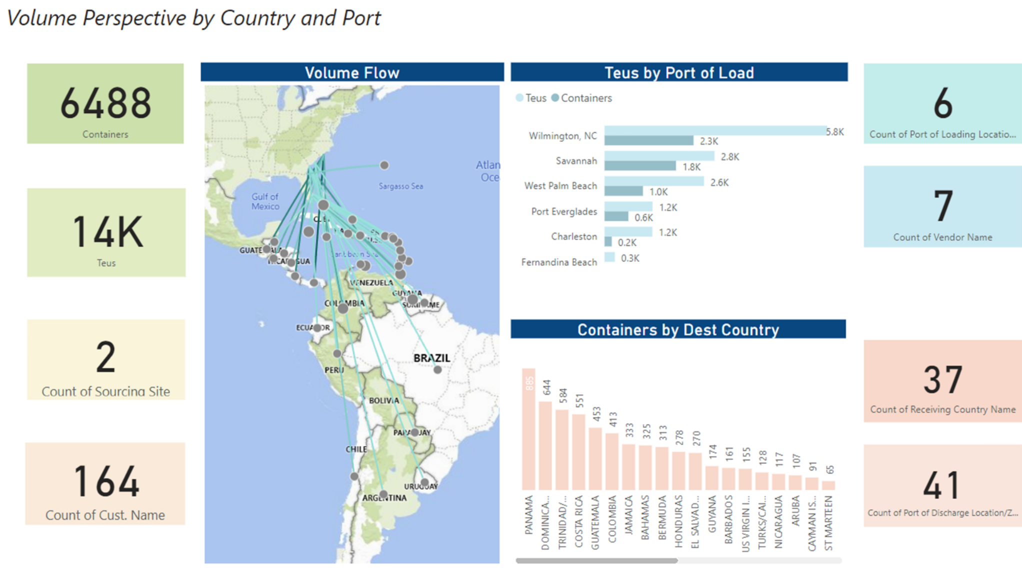


Figure 3. Volume Perspective by Country, Port of Load, and Port of Discharge.

We also analyzed the cost information, where we found a noticeable increase in prices of 15% on average compared with the previous year's negotiation and up to 78% for some lanes. We also discovered that the increase in transportation rates varies considerably depending on the lane and the equipment type (Figure A1).

5.2. Center of Gravity Analysis

We performed the center of gravity analysis for the mixing center location and consolidation of shipments to Caribbean islands. In order to recommend the optimal location for the mixing center, it was necessary to compile the data of the current supply warehouse and the existing ports of loading. Using the coordinates and the existing volume per facility, the new optimal location of the mixing center should be close to the ports of loading. The specific location, according to the center of gravity analysis, is South Carolina, compared to the existing location of the mixing center in North Carolina.

Considering the current container fill rate of 60%, we proposed a shipping consolidation in one of the islands to increase container utilization. In this case, we also invoked the center of gravity analysis on the eastern islands of lower volume to recommend consolidating volume in one island and avoiding inefficient containers that affect the cost and the traveled distance.

5.3. Modeling Results and Sensitivity Analysis

After implementing and running the MILP model using the Gurobi optimization package, we obtained the optimal volume flow from the supply warehouses to the mixing center, from the mixing center to the ports of loading, and from the ports of loading to the ports of discharge. The model used the current data of volume, costs, lead time, and expected service level of the FMCG company. The model incorporates critical synchromodal capabilities, including integration, flexibility, efficiency, and sustainability. The integration enables a holistic approach to supply chain decision-making by allowing decisions regarding mode choice, facility location, and flow allocation within the same model. The flexibility in this model is associated with modes shift and the ability to adjust the transportation flows within the network. The efficiency is tied to the model's objective function.

Since the objective function incorporates costs related to transportation, inventory, and the facility itself, the MILP model optimizes the supply chain design and flow allocation, taking into account the fundamental tradeoff between transportation and inventory holding costs. Even though sustainability elements are not incorporated explicitly, they are expected to be affected by the congruence between environmental costs and financial costs related to transportation and logistics. For example, the switch from truck to rail, increased capacity utilization, and improved container fill rate positively affect costs as well as emissions.

In order to analyze the results, we built a visualization dashboard using Power BI that provides the perspective of the optimal supply chain design. Figure 4 summarizes the comparison of the current scenario with the optimal one. The comparison considers the total costs from the supply warehouses to the mixing center, from the mixing center to the ports of loading, and from the ports of loading to the ports of discharge, as well as inventory holding cost and the cost of running the proposed mixing center. Similarly, Appendix A includes additional tabs with more specific information regarding the flow from the supply warehouse to the mixing center (Figure A2), from the mixing center to the port of loading (Figure A3), and from the port of loading to the port of discharge (Figure A4).

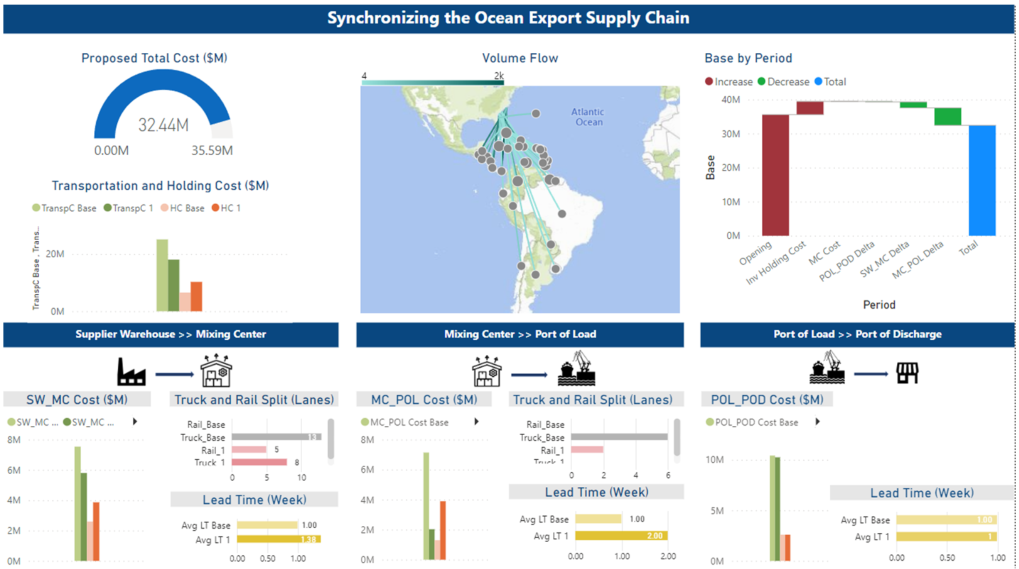
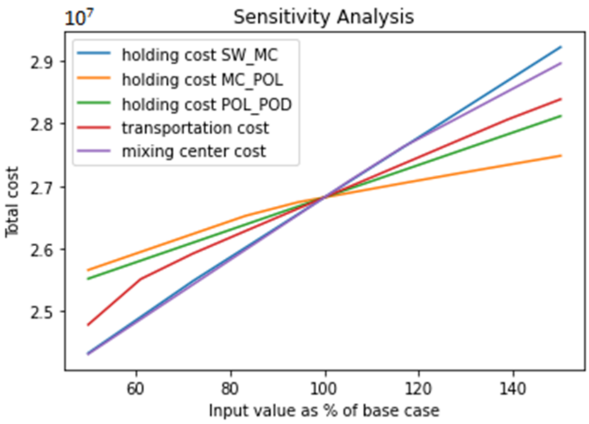


Figure 4. Summary of Base Scenario Compared to Optimization Scenarios. The legend corresponds to the notation introduced in Section 4.3.1.

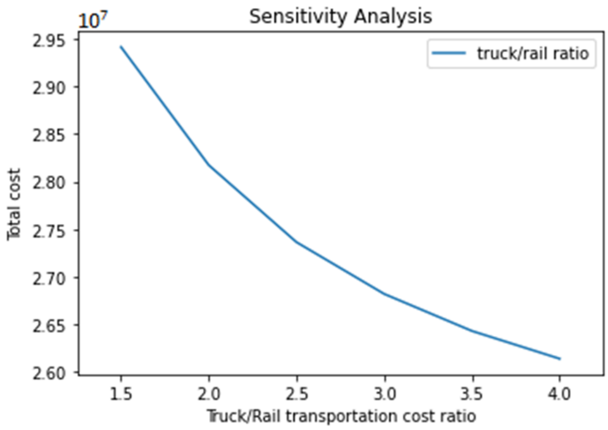
The optimal supply chain design discovered using the MILP model will allow the FMCG company to reduce total costs by 9%. The transportation costs can be reduced by 28% by the change in transportation mode of the inland freight from trucks to rail in certain routes from the supply warehouses to the mixing center and from the mixing center to the ports of loading. While this new volume allocation contributed positively from the transportation point of view, it increased the inventory holding by 60%, which is subject to a well-known tradeoff between transportation and holding costs [52,53]. Additionally, due to the switch from truck to rail in certain lanes, the optimal solution also increases the average lead time by 0.38 weeks from the supply warehouse to the mixing center and by 1 week from the mixing center to the port of loading. However, overall, the savings in transportation offset the impact of the inventory holding cost and longer lead time.

There are multiple variables in the MILP model that supply chain decision-makers can intervene in, namely, holding cost, transportation cost, and cost related to operating the mixing center. All of these three factors can improve through negotiation. In addition, holding costs can be reduced by better warehouse design and upgraded warehouse management systems. Transportation costs, in turn, can be reduced by upgrading the fleet and introducing more cost-efficient vehicles. Costs related to operating the mixing center can be reduced by upgrading equipment and automation.

Given limited company resources, a sensitivity analysis is performed to help decision-makers prioritize their investments for the most notable supply chain network improvement. For each model iteration, only one variable from the base case is modified to a range from 50% to 150% of the base case value, while the rest of the variables are kept constant at the base case value. Figure 5a shows the result of the sensitivity analysis of holding costs, transportation costs, and mixing center costs. The gradient of lines represents the sensitivities of variables. The result shows that holding cost SW_MC and mixing center cost are the most sensitive factors, followed by transportation cost and holding cost POL_POD, and the least sensitive factor is holding cost MC_POL. It implies that the company should spend most resources on improving holding costs from the supply warehouse to the mixing center and reducing the operation cost. Note that the sensitivity analysis lines are not always straight, which is a sign of nonlinearity. The inflection points represent a change in route choice, transportation mode, mixing center location, or volume allocation. Additionally, the base case MILP model used a truck-to-rail transportation cost ratio of 3, meaning the transportation cost of a truck is three times as expensive as rail. Therefore, another sensitivity analysis was conducted to test the robustness of our supply chain cost with respect to the transportation cost ratio. Figure 5b shows that the change in supply chain cost decreases as the truck-to-rail transportation cost ratio increases. This behavior aligns with our expectation as, at a ratio of 3, most of the optimized transportation mode is already rail, and there is little leeway for the model to switch from truck to rail to further reduce transportation costs as the ratio increases.



(a)



(b)

Figure 5. (**a**) Sensitivity analysis of holding costs, transportation cost, mixing center cost; (**b**) sensitivity analysis of truck-to-rail transportation cost ratio.

6. Discussion

Our study was conducted within the framework that addresses such main factors as cost, lead time, service level, flexibility, and sustainability to help companies identify the optimal network from the synchromodal standpoint. Figure 6 provides the graphical representation of the framework and its core components. Even though our study addressed the supply chain synchronization problem at a specific company, the proposed framework can be flexibly adapted to facilitate the decision-making for a similar multinational company.

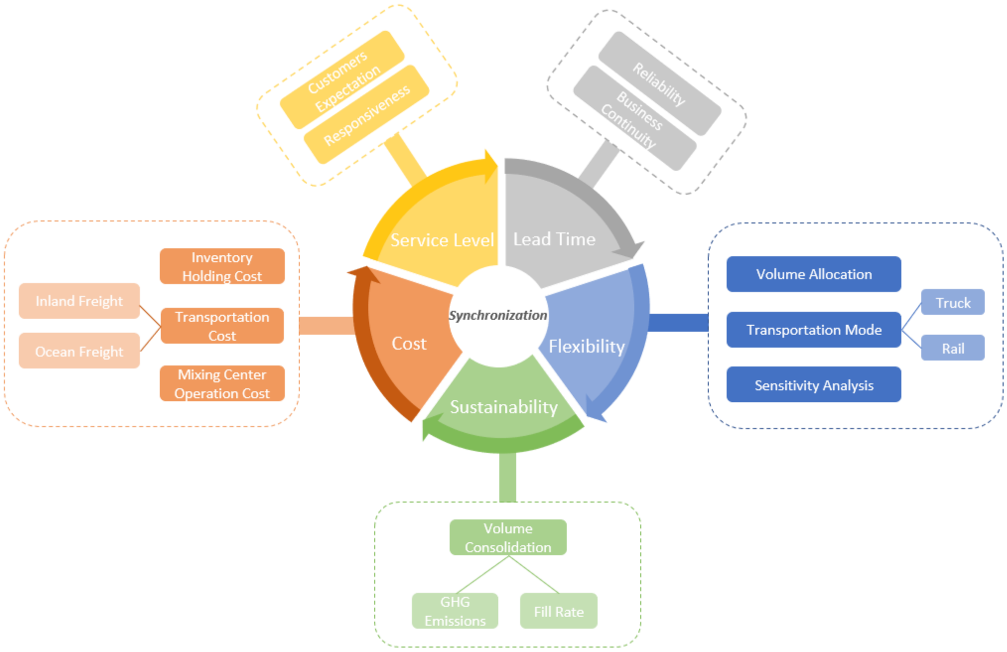


Figure 6. Framework for synchromodal supply chains.

At a high level, our study suggested that significant cost savings could be realized through synchromodality and optimization in a broader sense. Therefore, we emphasize that companies must challenge the status quo and leverage optimization models to consider alternative supply chain network designs. The following subsections shed light on critical insights, managerial implications, and promising directions for future research.

6.1. Insights and Managerial Implications

The modeling of the MILP to optimize the volume allocation provides versatility for companies to change assumptions and anticipate the impact of potential adjustments to the supply chain. When we ran different scenarios, we found that the FMCG company has an opportunity of reducing by 9% their costs.

We found that in order to optimize the supply chain costs for the FMCG company, it is essential to focus on a tradeoff between transportation and inventory holding costs. In the optimal design, the transportation costs were reduced by 28%, mainly by the change in transportation mode of the inland freight from trucks to rail in certain routes from the supply warehouses to the mixing center and from the mixing center to the ports of loading. In addition to the reduction in transportation costs, the introduction of synchromodality will enhance the flexibility of the FMCG company by allowing a switch between modes of transportation and enabling dynamic adaptation to changes in demand.

While the optimal volume allocation contributed positively from the transportation point of view, it increased the inventory holding cost by 60%. In addition, given the supply chain of the inland freight using rails compared to trucks for certain routes, the optimal solution also increases the lead time by 0.38 weeks from the supply warehouse to the mixing center and by 1 week from the mixing center to the port of loading. Nevertheless, the savings in transportation offset the impact of the inventory holding cost with the increased lead time.

We also tested the robustness of the supply chain costs with respect to the transportation cost ratio through sensitivity analysis. We found that the variation in supply chain cost decreases as the truck-to-rail transportation cost ratio increases. Our results showed that holding cost from the supply warehouses to the mixing center and mixing center cost are the most sensitive factors, followed by transportation cost and holding cost from the ports of loading to the ports of discharge, and the least sensitive factor is holding cost from the mixing center to the ports of loading. This fact implies that the company should spend most resources on improving the holding cost from the supply warehouse to the mixing center and on decreasing the mixing center operation cost.

6.2. Impacts on Sustainability

In 2020, global greenhouse gas emissions exceeded 50 billion carbon dioxide equivalents [54,55]. Logistics and freight transportation account for approximately 5.5% of all global carbon emissions. In its turn, over-the-road freight transportation, predominantly the trucking industry, constitutes more than half of this amount, with ocean freight at around 17% [56]. Indeed, the concept of sustainability is not limited to greenhouse gas emissions and encompasses multiple dimensions, including environmental, social, and economic factors. Even though all these dimensions are essential to creating thriving, healthy, diverse, and resilient communities for this generation and generations to come, they are outside of the scope of our study. However, in many cases, there is a congruence between environmental costs and financial costs related to transportation and logistics. Although vehicle emissions do vary significantly across different vehicle models and operating conditions, faster modes of transport (such as trucks) generally use greater amounts of fuel and have much larger carbon footprints compared to slower modes of transport (such as ships and railways) [27]. In addition, much of the time, vehicles do not carry a full load, and capacity underutilization or, simply speaking, moving empty space also consumes large amounts of fuel. For example, statistics from the EU suggest that trucks move empty 24% of the time, and only 57% are completely full when carrying a load [56]. So, both shippers and carriers, as well as the environment, bear the costs of underutilized capacity.

Our study sees these issues as a "low-hanging fruit". Synchromodality allows the switch from trucks to rail and better container utilization through flow consolidation. As a result, the company can notably reduce the carbon footprint and improve sustainability by saving money simultaneously. Additionally, apart from mode choices, transportation performance in terms of costs and emissions is strongly determined by the network design. In distribution networks, this refers, in particular, to the location of mixing centers or other transport hubs such as distribution centers or cross-docks [57]. Due to the optimization of the mixing center location and consolidation of the flow, shipments with different origins and different destinations will be brought together in a "milk run", a tour with shared capacity over some portion of the route. Consolidation leads to a smaller carbon footprint per shipment compared to sending partially full vehicles directly. Additionally, consolidation enables the use of larger, more fuel-efficient vehicles for movements between ports and mixing centers [58].

The container fill rate prior to optimization was 62%. Therefore, the grouping of the ports of discharge in the Caribbean islands also represents an opportunity for the company to increase container utilization and reduce the emissions related to inland freight and ocean transportation. We recommend that the company pays attention to the container fill rate and consider the consolidation of volume when possible to decrease the costs, reduce the traveled distance, and ultimately minimize the impact on the environment.

6.3. Synchromodality in Light of Digital Transformation

The pervasive commoditization in the FMPG industry turns logistics capabilities into a key driver of competitiveness. Operating under demand uncertainty and risks of disruptions, businesses have to develop such critical capabilities as flexibility, efficiency, and sustainability by balancing margin-oriented objectives and market responsiveness in a real-time data-driven setting [59]. It follows the famous Leon C. Megginson quote paraphrasing Charles Darwin: "It is not the strongest of the species that survives, nor the most intelligent, but it is the one that is most adaptable to change" [60]. Therefore, to stay competitive, companies have to gain the capability to dynamically adjust toward changes in volume, cost structure, and consumer preferences [61].

Synchromodality provides cost-efficiency through flow consolidation and flexibility associated with the mode switch, allowing companies to adapt and adjust in a timely manner. However, the true potential of synchromodality is unlocked if and only if all the critical stakeholders obtain accurate real-time data, identify weaknesses, and streamline processes. In this regard, an essential aspect of synchromodality is its connection with information and communication technologies as well as the ongoing supply chain digitalization trend [62]. In light of digitalization, companies are paying particular attention to emerging technologies and data-centric solutions that enable real-time connectivity, flexibility, and visibility at a highly granular level [61,63–65]. Emerging digital technologies such as the Internet of Things, AI, 5G, cloud, and edge computing applied in combination with synchromodal operations have the potential to revolutionize value chains by closing gaps between supply chain management, logistics, and transportation.

6.4. Limitations and Directions for Future Research

Given the computational and business process complexity that arises from the multi-criteria nature of the problem, our study has certain limitations. Although the proposed solution positively contributes to sustainability, the exact environmental impact still needs to be quantified by calculating the carbon dioxide equivalent associated with transportation and inventory lifecycle. In addition, the constraints related to emissions can be incorporated into the MILP model explicitly. Additionally, the connection between synchromodality, digital processes, and emerging technologies is a promising direction for future research.

The MILP model, a pivotal part of the proposed framework, has been tested based on the data provided by the FMCG company. In this regard, it is important to point out that the FMCG company deals with a very mature product, so the network is not subject to changes, demand is quite stable, and the scale of the problem is small with regard to the computational budget. If another company decides to adopt the proposed framework, the inputs should be checked for feasibility, and the problem scale should be taken into account. If the company adopting the proposed framework deals with a significantly larger network, cuts and various heuristics to boost computation performance should be explored because MILP models are NP-hard [66]. Therefore, we also postulate the analysis of computational performance as another promising direction for future research.

Additionally, the proposed framework for synchronized supply chain design uses a deterministic MILP model, which has many limitations in light of real-world uncertainty. In our case, the FMCG company that provided the data deals with mature products that have very stable demand. Even though the current model is deterministic, it uses the standard deviation of demand as one of the inputs making safety stock proportional to the standard deviation of demand at ports of discharge. However, the stochastic model has the potential to provide more reliable results and facilitate decision-making in light of uncertainty. Therefore, the adoption of stochastic optimization [67] is worth exploring in future research.

Since seminal works emphasize the dynamicity and real-time coordination as crucial aspects of synchromodality [2,17,31], the proposed framework will significantly benefit from adopting Bayesian information updating [68], as well as Bayesian decisions [69]. This modification will allow using model inputs not only based on historical observations but also by taking into account the real-time situation.

7. Conclusions

Increasing ocean freight costs and volatility have attracted global attention. As a result, multinational companies are looking to offset the rising cost. In order to approach this issue, our study proposes a framework for companies to drive synchromodality in their ocean export supply chain.

The proposed framework is tested using data from a leading fast-moving consumer goods company. The supply chain network under consideration is complex and includes 62 nodes, 284 possible arcs, and 6488 container shipments per year. After analyzing ocean freight costs, we validated a significant price increase of 15% compared to the previous year. We carried out an initial assessment of the current mixing center location using a center of gravity analysis. This study concluded that companies could reap financial benefits by locating a mixing center closer to ports rather than supply warehouses since ports are notably less scattered than supply warehouses. Next, we developed a MILP model to recommend mixing center location and shipping routes to optimize overall supply chain cost, including transportation, inventory holding, and mixing center costs. The rail option was added to the existing truck option for inland transport from the supply warehouse to ports of loading. Although having multiple modes of transportation adds flexibility to the model, the model also proved that incorporating synchromodality in the ocean export supply chain could reduce the overall cost by 9%.

Considering that the company has many decisions to make along the supply chain but limited resources on hand, we conducted a sensitivity analysis of the MILP model to identify the most effective points of intervention. We recommended the company focus on holding costs at the supply warehouse, followed by transportation costs from ports of loading to ports of discharge. At the same time, the holding cost at the mixing center and transportation to the ports of loading appeared to be less sensitive factors.

Even though our study addressed the supply chain synchronization problem at a specific company, the proposed framework can be flexibly adapted to facilitate the decision-making. Our study suggested that significant cost savings could be realized through synchromodality and optimization in a broader sense. Therefore, we emphasize that companies must challenge the status quo and leverage optimization models to consider alternative supply chain network designs.

It is important to point out that the FMCG company deals with a very mature product, so the network is not subject to changes, demand is quite stable, and the scale of the problem is small with regard to the computational budget. If another company decides to adopt the proposed framework, the inputs should be checked for feasibility, and the problem scale should be taken into account. If the company adopting the proposed framework deals with a significantly larger network, cuts and various heuristics to boost computation performance should be explored because MILP models are NP-hard.

Author Contributions: Conceptualization, M.J.S., I.J., Y.L. and M.S.R.M.; methodology, M.J.S., Y.L., I.J. and M.S.R.M.; validation, I.J. and Y.L.; data curation, I.J., Y.L. and M.S.R.M.; writing—original draft preparation, I.J., M.J.S., M.S.R.M. and Y.L.; writing—review and editing, M.J.S. and I.J.; visualization, M.S.R.M., Y.L. and I.J.; supervision, M.J.S. and I.J.; project administration, M.J.S. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

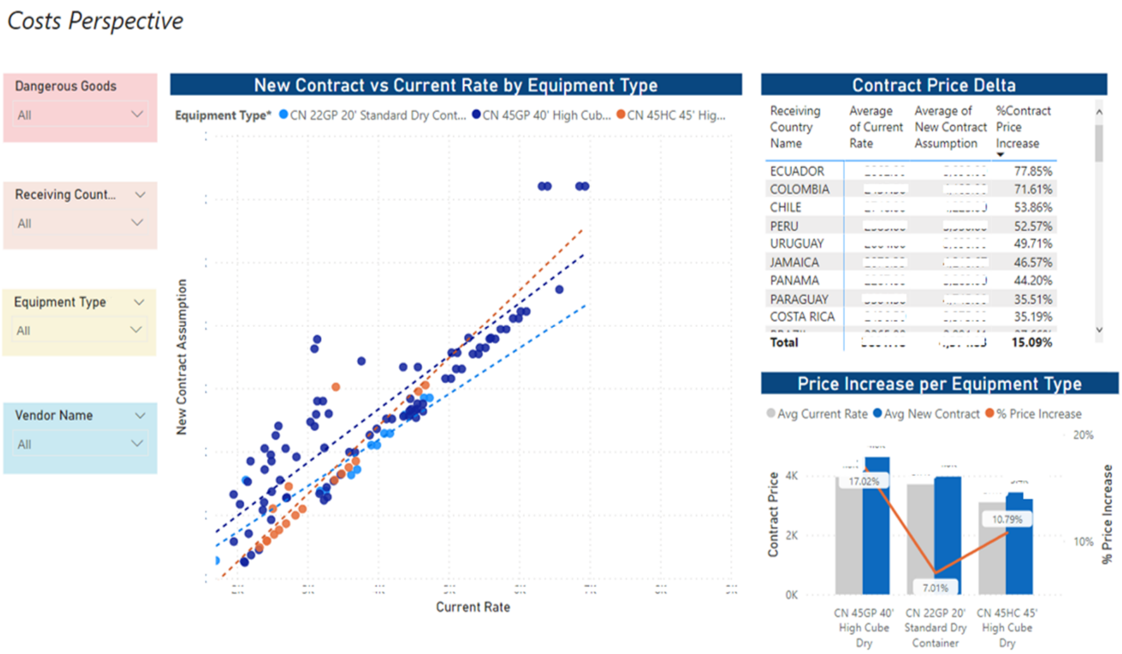

Figure A1. Costs Perspective. The legend corresponds to the notation introduced in Section 4.3.1. The values for current rates, new contract assumptions, and costs are sensitive data and intentionally covered.

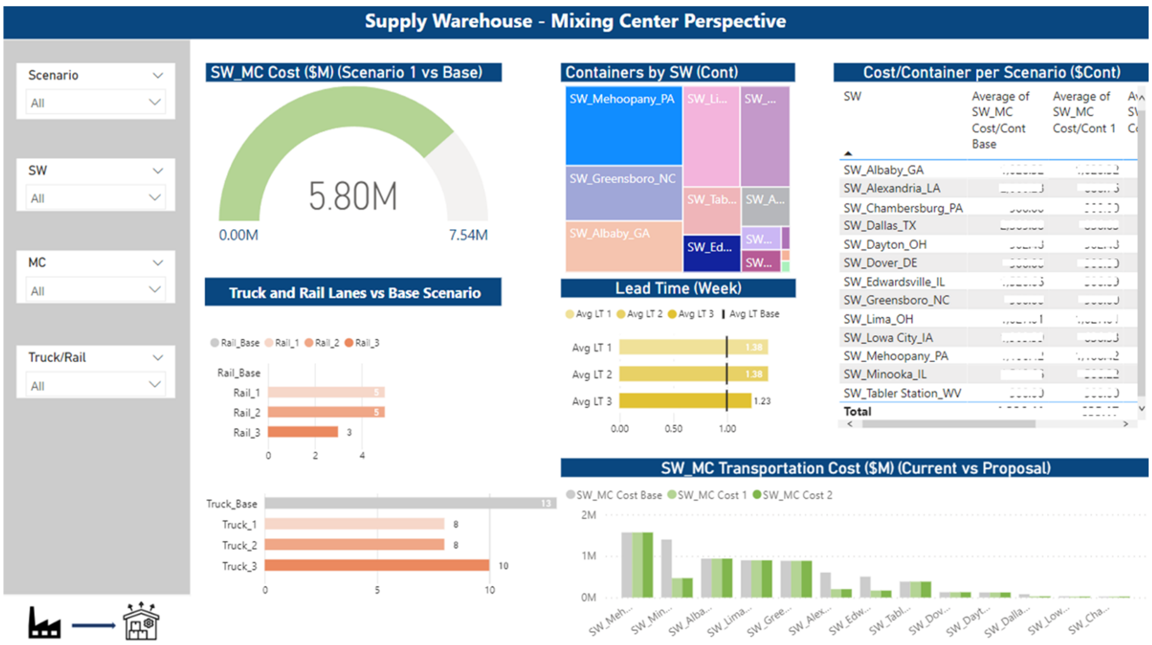

Figure A2. Summary of Supply Warehouse to Mixing Center Perspective. The legend corresponds to the notation introduced in Section 4.3.1. The values for current rates, new contract assumptions, and costs are sensitive data and intentionally covered.

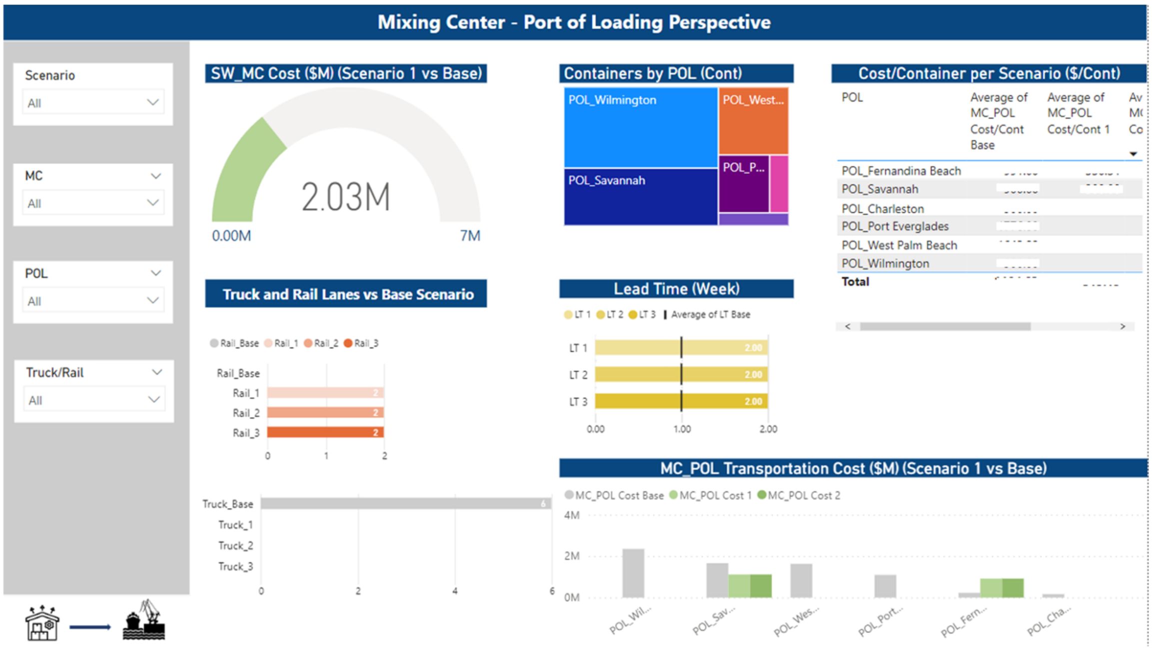

Figure A3. Summary of Mixing Center to Port of Loading Perspective. The legend corresponds to the notation introduced in Section 4.3.1. The values for current rates, new contract assumptions, and costs are sensitive data and intentionally covered.

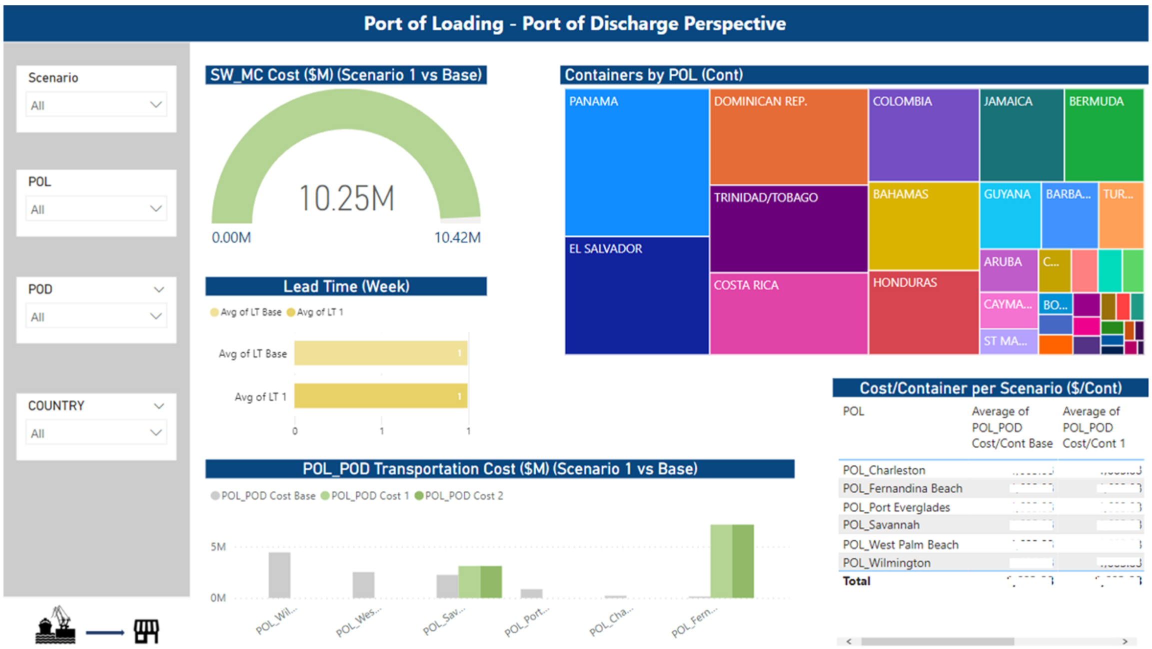

Figure A4. Summary of Port of Loading to Port of Discharge Perspective. The legend corresponds to the notation introduced in Section 4.3.1.

References

1. Watson, M.; Lewis, S.; Cacioppi, P.; Jayaraman, J. *Supply Chain Network Design: Applying Optimization and Analytics to the Global Supply Chain*; Pearson Education: London, UK, 2013.
2. Acero, B.; Saenz, M.J.; Luzzini, D. Introducing synchromodality: One missing link between transportation and supply chain management. *J. Supply Chain. Manag.* **2022**, *58*, 51–64. [CrossRef]
3. Chankov, S.M.; Becker, T.; Windt, K. Towards definition of synchronization in logistics systems. *Procedia CIRP* **2014**, *17*, 594–599. [CrossRef]

4. Osipov, G.V.; Kurths, J.; Zhou, C. *Synchronization in Oscillatory Networks*; Springer Science & Business Media: Berlin/Heidelberg, Germany, 2007.
5. Pereira, M.M.; Frazzon, E.M. A data-driven approach to adaptive synchronization of demand and supply in omni-channel retail supply chains. *Int. J. Inf. Manag.* **2021**, *57*, 102165. [CrossRef]
6. Fransoo, J.; Lee, C. The Critical Role of Ocean Container Transport in Global Supply Chain Performance. *J. Wiley Online Libr.* **2012**, *22*, 253–268. [CrossRef]
7. United Nations Conference on Trade and Development. Review of Maritime Transport. 2021. Available online: https://unctad.org/system/files/official-document/rmt2021_en_0.pdf (accessed on 4 February 2023).
8. Organization for Economic Co-operation and Development. International Trade during the COVID-19 Pandemic: Big Shifts and Uncertainty. Available online: https://www.oecd.org/coronavirus/policy-responses/international-trade-during-the-covid-19-pandemic-big-shifts-and-uncertainty-d1131663/ (accessed on 4 February 2023).
9. United States International Trade Commission. The Impact of the COVID-19 Pandemic on Freight Transportation Services and U.S. Merchandise Imports. Available online: https://www.usitc.gov/research_and_analysis/tradeshifts/2020/special_topic.html (accessed on 4 February 2023).
10. Drewry Index. World Container Index. Available online: https://www.drewry.co.uk/supply-chain-advisors/supply-chain-expertise/world-container-index-assessed-by-drewry (accessed on 4 February 2023).
11. Giusti, R.; Manerba, D.; Bruno, G.; Tadei, R. Synchromodal logistics: An overview of critical success factors, enabling technologies, and open research issues. *Transp. Res. Part E Logist. Transp. Rev.* **2019**, *129*, 92–110. [CrossRef]
12. Liu, Y.; Li, M.; Zhu, Z. Simulated Annealing Sales Combining Forecast in FMCG. In Proceedings of the 2013 IEEE 10th International Conference on E-Business Engineering, Coventry, UK, 11–13 September 2013. [CrossRef]
13. Keller, K.L. Brand synthesis: The multidimensionality of brand knowledge. *J. Consum. Res.* **2003**, *29*, 595–600. [CrossRef]
14. Ramirez, M.; Li, Y.; Jackson, I.; Saenz, M.J. Supply Chain Synchronization: A Choice That Became a Must. Supply Chain Management Review 2022. Available online: https://www.scmr.com/article/supply_chain_synchronization_a_choice_that_became_a_must (accessed on 4 February 2023).
15. Li, Y.; Ramirez, M. Synchronization of Ocean Export Supply Chain. Capstone Thesis 2022. DSpace. MIT Libraries. Available online: https://dspace.mit.edu/handle/1721.1/142949 (accessed on 4 February 2023).
16. Dong, C.; Boute, R.; McKinnon, A.; Verelst, M. Investigating synchromodality from a supply chain perspective. *Transp. Res. Part D* **2018**, *61*, 42–57. [CrossRef]
17. Reis, V. Should we keep on renaming a+ 35-year-old baby? *J. Transp. Geogr.* **2015**, *46*, 173–179. [CrossRef]
18. Crainic, T.G.; Kim, K.H. Intermodal transportation. In *Handbooks in Operations Research and Management Science*; Barnhart, I.C., Laporte, G., Eds.; Elsevier: Amsterdam, The Netherlands, 2007; pp. 467–537.
19. European Conference of Ministers of Transport. *Report on the Current State of Combined Transport in Europe*; OECD Publications: Paris, France, 1998.
20. European Commission. *Keep Europe Moving—Sustainable Mobility for Our Continent*; European Commission: Brussels, Belgium, 2006; ISBN 92-79-02312-8.
21. Burnette, M.; Meline, J.; Pellathy, D. End-to-End Supply Chain Synchronization Orchestrating a Winning Strategy. Available online: https://supplychainmanagement.utk.edu/research/white-papers/2020-04-synchronization/ (accessed on 4 February 2023).
22. Bagchi, P.K.; Chun Ha, B.; Skjoett-Larsen, T.; Boege Soerensen, L. Supply chain integration: A European survey. *Int. J. Logist. Manag.* **2005**, *16*, 275–294. [CrossRef]
23. Nikfarjam, H.; Rostamy-Malkhalifeh, M.; Mamizadeh-Chatghayeh, S. Measuring supply chain efficiency based on a hybrid approach. *Transp. Res. Part D Transp. Environ.* **2015**, *39*, 141–150. [CrossRef]
24. Hopp, W.J.; Spearman, M.L. *Factory Physics*; Waveland Press: Long Grove, IL, USA, 2011.
25. Keeble, B.R. The Brundtland report: 'Our common future'. *Med. War* **1988**, *4*, 17–25. [CrossRef]
26. Martins, C.L.; Pato, M.V. Supply chain sustainability: A tertiary literature review. *J. Clean. Prod.* **2019**, *225*, 995–1016. [CrossRef]
27. Blanco, E.E.; Sheffi, Y. Green Logistics. In *Sustainable Supply Chains*; Bouchery, Y., Corbett, C., Fransoo, J., Tan, T., Eds.; Springer Series in Supply Chain Management; Springer: Cham, Switzerland, 2017; Volume 4. [CrossRef]
28. Verweij, K. Synchromodal transport: Thinking in hybrid cooperative networks. In *Logistics Yearbook*; Van Der Sterre, P.J., Ed.; Capgemini: Paris, France, 2011; pp. 75–88.
29. Lu, M. Synchromodality for enabling smart transport hubs. In Proceedings of the International Conference on Traffic and Transport Engineering, Belgrade, Serbia, 27–28 November 2014; pp. 875–880.
30. Oonk, M. Smart logistics corridors and the benefits of intelligent transport systems. In Proceedings of the Transport Research Arena 2014, Paris, France, 14–17 April 2014.
31. Hofman, W. Control tower architecture for multi- and synchromodal logistics with real time data. In Proceedings of the 5th International Conference on Information Systems, Logistics and Supply Chain (ILS 2014), Breda, The Netherlands, 24–27 August 2014.
32. Singh, P. Developing a service oriented IT platform for synchromodal transportation. In *On the Move to Meaningful Internet Systems: OTM 2014 Workshops*; Springer: Berlin/Heidelberg, Germany, 2014; pp. 30–36.

33. Zhang, M.; Pel, A.J. Synchromodal hinterland freight transport: Model study for the port of Rotterdam. *J. Transp. Geogr.* **2016**, *52*, 1–10. [CrossRef]
34. Ferjani, A.; El Yaagoubi, A.; Essaghir, Y.; Boukachour, J.; Duvallet, C. Towards the Implementation of Synchromodality along the Seine Axis. In Proceedings of the 2022 IEEE 6th International Conference on Logistics Operations Management (GOL), Strasbourg, France, 29 June 2022–1 July 2022; pp. 1–8.
35. Van Riessen, B.; Negenborn, R.R.; Lodewijks, G.; Dekker, R. Impact and relevance of transit disturbances on planning in intermodal container networks using disturbance cost analysis. *Marit. Econ. Logist.* **2015**, *17*, 440–463. [CrossRef]
36. Rivera, A.E.P.; Mes, M.R. Anticipatory freight selection in intermodal long-haul round-trips. *Transp. Res. Part E Logist. Transp. Rev.* **2017**, *105*, 176–194. [CrossRef]
37. Li, L.; Negenborn, R.R.; De Schutter, B. Distributed model predictive control for cooperative synchromodal freight transport. *Transp. Res. Part E Logist. Transp. Rev.* **2017**, *105*, 240–260. [CrossRef]
38. Zhao, L.; Zhao, Y.; Hu, Q.; Li, H.; Stoeter, J. Evaluation of consolidation center cargo capacity and loctions for China railway express. *Transp. Res. Part E Logist. Transp. Rev.* **2018**, *117*, 58–81. [CrossRef]
39. Qu, W.; Rezaei, J.; Maknoon, Y.; Tavasszy, L. Hinterland freight transportation replanning model under the framework of synchromodality. *Transp. Res. Part E Logist. Transp. Rev.* **2019**, *131*, 308–328. [CrossRef]
40. Guo, W.; Atasoy, B.; van Blokland, W.B.; Negenborn, R.R. Global synchromodal transport with dynamic and stochastic shipment matching. *Transp. Res. Part E Logist. Transp. Rev.* **2021**, *152*, 102404. [CrossRef]
41. Jackson, I. AutoML Approach to Stock Keeping Units Segmentation. *J. Theor. Appl. Electron. Commer. Res.* **2022**, *17*, 1512–1528. [CrossRef]
42. Lester, R. What Is Lead Time, Why Is It Important, and How Do You Reduce It? Available online: https://www.linkedin.com/pulse/what-lead-time-why-important-how-do-you-reduce-roland-lester/ (accessed on 4 February 2023).
43. Sharman, J. 8 Ways to Reduce Supply Chain Lead Times. Available online: https://www.mcl.bz/blog/ways-to-reduce-supply-chain-lead-times (accessed on 4 February 2023).
44. Becker, L.T.; Gould, E.M. Microsoft power BI: Extending excel to manipulate, analyze, and visualize diverse data. *Ser. Rev.* **2019**, *45*, 184–188. [CrossRef]
45. Schniederjans, M.J. *International Facility Acquisition and Location Analysis*; Greenwood Publishing Group: Westport, CT, USA, 1999.
46. Bertsimas, D.; Tsitsiklis, J.N. *Introduction to Linear Optimization*; Athena Scientific: Belmont, MA, USA, 1997; Volume 6, pp. 479–530.
47. Luathep, P.; Sumalee, A.; Lam, W.H.; Li, Z.C.; Lo, H.K. Global optimization method for mixed transportation network design problem: A mixed-integer linear programming approach. *Transp. Res. Part B Methodol.* **2011**, *45*, 808–827. [CrossRef]
48. Zhen, L.; Huang, L.; Wang, W. Green and sustainable closed-loop supply chain network design under uncertainty. *J. Clean. Prod.* **2019**, *227*, 1195–1209. [CrossRef]
49. Conforti, M.; Cornuéjols, G.; Zambelli, G. *Integer Programming*; Springer: Berlin/Heidelberg, Germany, 2014; Volume 271, pp. 67–70.
50. Rao, S.S. *Engineering Optimization: Theory and Practice*; John Wiley & Sons: Hoboken, NJ, USA, 2019.
51. Achterberg, T. What's New in Gurobi 9.0. Webinar Talk. Available online: https://www.gurobi.com/wp-content/uploads/Whats-New-in-Gurobi-9.1.pdf (accessed on 4 February 2023).
52. Baumol, W.J.; Vinod, H.D. An inventory theoretic model of freight transport demand. *Manag. Sci.* **1970**, *16*, 413–421. [CrossRef]
53. Sheffi, Y.; Eskandari, B.; Koutsopoulos, H.N. Transportation mode choice based on total logistics costs. *J. Bus. Logist.* **1988**, *9*, 137–154.
54. Ritchie, H.; Roser, M.; Rosado, P. CO_2 and Greenhouse Gas Emissions. Our World in Data. 2020. Available online: https://ourworldindata.org/greenhouse-gas-emissions (accessed on 4 February 2023).
55. Gates, B. *How to Avoid a Climate Disaster: The Solutions We Have and the Breakthroughs We Need*; Knopf: New York, NY, USA, 2021.
56. World Economic Forum. 2009. Available online: https://www3.weforum.org/docs/WEF_LT_SupplyChainDecarbonization_Report_2009.pdf (accessed on 4 February 2023).
57. Martínez, J.C.V.; Fransoo, J.C. Green facility location. In *Sustainable Supply Chains*; Springer: Cham, Switzerland, 2017; pp. 219–234.
58. Sheffi, Y. *Balancing Green: When to Embrace Sustainability in a Business (and When Not to)*; MIT Press: Cambridge, MA, USA, 2018.
59. Saenz, M.J.; Borrella, I.; Revilla, E. Digital Supply Chain Transformation: Aligning Operations and Strategy. Supply Chain Management Review. 2022. Available online: https://digitalsc.mit.edu/wp-content/uploads/2022/03/Saenz-et-al_SCMR2203_Framework-Digital-SC-Transformation.pdf (accessed on 4 February 2023).
60. Megginson, L.C. Lessons from Europe for American business. *Southwest. Soc. Sci. Q.* **1963**, *44*, 3–13.
61. Rolf, B.; Jackson, I.; Müller, M.; Lang, S.; Reggelin, T.; Ivanov, D. A review on reinforcement learning algorithms and applications in supply chain management. *Int. J. Prod. Res.* **2022**, *60*, 1–29. [CrossRef]
62. Saenz, M.J. How the Pandemic Could Remake Supply Chain's Digital Future. Supply Chain 24/7 2020. Available online: https://www.supplychain247.com/article/how_the_pandemic_could_remake_supply_chains_digital_future (accessed on 4 February 2023).
63. Choi, T.M.; Wallace, S.W.; Wang, Y. Big data analytics in operations management. *Prod. Oper. Manag.* **2018**, *27*, 1868–1883. [CrossRef]

64. Saenz, M.J.; Rice, J.; Cottrill, K. Do You Have the DT's? Why It's Time to Bring Digital Transformation down to Earth. Supply Chain Management Review 2019. Available online: https://www.scmr.com/article/do_you_have_the_dts_why_its_time_to_bring_digital_transformation_down_to_ea (accessed on 4 February 2023).
65. Saenz, M.J.; Cottrill, K. Navigating the Road to Digital Transformation. Supply Chain Management Review 2019. Available online: https://www.scmr.com/article/navigating_the_road_to_digital_supply_chain_transformation (accessed on 4 February 2023).
66. Nemhauser, G.L.; Wolsey, L.A. *Integer and Combinatorial Optimization*; Wiley: New York, NY, USA, 1988; p. 118.
67. Fu, M.C. Optimization for simulation: Theory vs. practice. *INFORMS J. Comput.* **2002**, *14*, 192–215. [CrossRef]
68. Choi, T.M.; Li, D.; Yan, H. Optimal two-stage ordering policy with Bayesian information updating. *J. Oper. Res. Soc.* **2003**, *54*, 846–859. [CrossRef]
69. Ma, W.J. Bayesian decision models: A primer. *Neuron* **2019**, *104*, 164–175. [CrossRef] [PubMed]