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Transport Networks in More Responsive and Sustainable Supply Chains

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Master Thesis

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To my family

Abstract

The recent disruptions in global trade and logistics have underscored the crucial role of resilient and flexible supply chain operations across various sectors. These recent disruptions have shed light on the critical vulnerabilities in multimodal transportation networks, emphasising the importance of developing stronger resiliency, adaptability, and sustainability strategies.

One of the primary challenges in this domain is understanding and predicting supply chain behaviour under conditions of uncertainty, as well as managing capacity effectively to mitigate associated risks. To tackle this issue, this dissertation introduces a simulation-based approach with two main objectives: i) to comprehend the dynamics of multimodal supply chain networks, identify weaknesses and test the robustness of the supply chain, and ii) to aid decision-making processes aimed at enhancing resilience and flexibility through strategic capacity management.

This dissertation contributes to the field of supply chain management by proposing innovative solutions to enhance the resilience and sustainability of multimodal transportation networks. The findings align with and expand upon existing literature, offering practical strategies and empirical evidence to improve supply chain performance. Future research directions include exploring additional scenarios, integrating emerging technologies, and validating the simulation model through real-world case studies to further develop resilient and sustainable supply chain networks.

Keywords: Logistics; Supply Chain; Resilient Supply Chain; Multimodal Transportation Network; Robustness; Sustainability; Simulation-based Decision Support Systems; Supply Chain Management.

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List of abbreviations

ABM	Agent-Based Modeling
AI	Artificial Intelligence
ARFC	Atlantic Rail Freight Corridor
CSCMP	Council of Supply Chain Management Professionals
DC	Distribution Center
DES	Discrete Event Simulation
DSS	Decision Support System
FIFO	First In First Out
FTL	Full Truck Load
GSCM	Green Supply Chain Management
NGO	Non-Governmental Organization
TEU	Twenty-foot Equivalent Unit
SC	Supply Chain
SCM	Supply Chain Management
SD	System Dynamics
SDG	Sustainable Development Goals
SL	Service Level
SSCM	Sustainable Supply Chain Management
RMU	Relative Measurement Unit

1. Introduction

This first chapter introduces the dissertation theme, "Transport Networks in More Responsive and Sustainable Supply Chains".

1.1 Contextualisation

Current Supply Chains (SC) have evolved into sophisticated distribution networks of many players, interconnected activities, products, and information exchanges. As the pace of globalisation accelerates and consumer demands shift unpredictably, the risks and potential SC disruptions have significantly increased. This evolving context highlights the need for a special focus on SC efficiency and resilience. Defined as the ability to foresee, adapt, and quickly recover from disruptions, SC resilience has become a vital area of research in recent years, assuming a key role in enduring long-term sustainable growth (Rahman et al., 2022). Supply chain efficiency and resiliency are critical to enduring long-term sustainable growth.

In this regard, transportation and logistics infrastructures could significantly impact SC performance and its vulnerabilities to uncertain conditions. These are valuable components for achieving a more sustainable and responsive SC (Gast et al., 2022). The transportation sector supports global commerce and connectivity, offering vital links between suppliers and markets worldwide. The shift towards multimodal and multimodal transportation strategies plays a crucial role in enhancing the effectiveness and sustainability of supply chains.

According to Brochado et al., 2024, multimodality in the supply chain distribution process involves using various transportation modes—such as rail, truck, ship, barge, and aircraft—for a single shipment. This is managed under one bill of lading or similar contract, where a single transportation company oversees and takes full responsibility for the entire shipping process. In contrast, multimodality integrates and coordinates different transportation modes within a door-to-door supply chain. Each mode is operated by a different carrier under separate contracts, offering cost savings. Clients specify the origin and destination, but the routes and transportation modes are flexible as long as they meet the demand (Brochado et al., 2024).

Nevertheless, as scientific advancements and technological innovations emerge, the intricacy of managing comprehensive supply chains intensifies alongside growing societal demands, stringent regulations, and swiftly evolving markets (Silva, 2022). Consequently, this places increased pressure on industries across the board to enhance cost-efficiency and agility.

1.2 Motivation

The design and management of transport networks are at a crossroads as it seeks to develop efficient multimodal strategies to cope with the current market diversity while accounting for today's highly dynamic and uncertain business context.

The need for efficient, responsive supply chains is underscored by the industry's inherent vulnerabilities to unexpected disruptions. Current supply chains often remain highly disconnected, hindering organizations from implementing collaborative practices and performance monitoring essential for improved responsiveness and sustainable operations. Transportation networks play a crucial role in supply chain risk management by providing the necessary logistics infrastructure to accommodate, operate, and connect multiple agents and stakeholders reliably. Therefore, the design and management of transportation networks significantly impact overall supply chain performance and global vulnerabilities. Studying and understanding the links and relationships between transportation networks and supply chain design and management from an integrated perspective can be a powerful enabler of risk mitigation strategies and a lever for achieving higher levels of operational sustainability (Dong et al., 2018).

Disruptions, characterized by their multifaceted and sporadic nature, make them exceptionally challenging to predict and manage. This was clearly accentuated by the COVID-19 pandemic, which caused worldwide logistical chaos, and by Brexit, which added a new layer of geopolitical complexity and regulatory constraints (ESPON, 2021). Both instances are examples of disruptions that can have far-reaching effects on the stability and functionality of supply systems.

This dissertation seeks to develop a Decision Support System (DSS) to aid better decision-making regarding multimodal transportation routes across the supply chain and assess the SC performance under different conditions. This platform will seek to balance the transportation supply chain, providing it with the flexibility and sustainability required to cope with multiple uncertainties. By doing so, it will address the vulnerabilities of the current system, which, despite the existence of decision-support technologies designed to improve efficiency, resilience, and sustainability, remains susceptible to possible future disruptions. Therefore, this study seeks to address the compelling need for an integrated supply chain solution capable of meeting the current SC management challenges through proactive development and use of multimodal solutions.

1.3 Objectives

This dissertation aims to address the previously identified challenges by developing a simulation-based platform to support high-level decision-making in network design and capacity management for multimodal logistics. This platform is expected to aid decision-making towards increased supply chain efficiency, sustainability, and resilience by exploring different multimodal strategies and understanding how these strategies can contribute to better performance in an uncertain context. In this regard, two specific objectives were defined: (i) to analyse the impacts of different transportation modes on global supply chain performance considering multiple sustainability dimensions (economic, environmental, and social), and (ii) to assess the supply chain performance under different scenarios.

Regarding the first objective, the primary purpose is to investigate how different combinations of transportation modes (train, truck, and boat) impact the overall performance and sustainability of the supply chain. To achieve this, various key performance indicators (KPIs) will be defined to assess critical dimensions such as operational costs, carbon emissions, and delivery service levels.

The second objective is to understand the supply chain dynamics under different scenarios and how different transportation network strategies can enhance global supply chain resiliency.

Unlike standard optimisation models, the simulation approach used in this study allows for a more in-depth understanding of the multimodal system and provides performance estimates and projections. The research will gain insights into the supply chain's behaviour by investigating diverse alternatives and scenarios and drawing suggestions regarding the most promising strategies towards more resilient and sustainable SC.

1.4 Methodological approach

As previously described, the main goal of the work developed in this dissertation is to build a simulation-based platform to address the challenges and high-level decision-making in the supply chain network design and capacity management under uncertainty.

A well-defined simulation study approach is critical to developing effective and successful models (Law, 2022). Following this author's guidelines, a methodological sequential approach was pursued to address the problem.

A detailed literature review was conducted to contextualise and appropriately formulate the subject in question. This analysis describes the problem at hand, as well as the main parameters, constraints, and simplifications that result in a close-to-reality model of a supply chain and transportation network. After developing a conceptual model, a simulation model based on Discrete Event Simulation (DES) and Agent Base Simulation (ABS) techniques is created to simulate and test the supply chain under different conditions. A case study is then generated for model validation by entering the required data and model parameters. Following model validation, multiple alternatives will be developed, considering different multimodal transport strategies to evaluate which strategies perform better in different scenarios (Law, 2022).

1.5 Dissertation Structure

This dissertation has been organised into six chapters, each detailing a specific project phase regarding the impact of multimodal transportation on supply chain management.

Chapter 1 introduces the concept of multimodal transportation and outlines the goals and motivations for this study.

Chapter 2 provides a literature review of the fundamental issues, offering the necessary knowledge required to complete this dissertation. It covers supply chain management concepts, special concerns for multimodal transportation within supply chains, and the significance of simulation in supply chain analysis.

Chapter 3 presents the methodology adopted to develop the decision support tool, including the problem formulation, conceptual model, and simulation model of multimodal transport within the supply chain.

Chapter 4 provides a detailed analysis of the different alternatives considered in the study. It describes and compares the performance of each alternative in terms of service levels, inventory management, costs, and sustainability.

Chapter 5 evaluates the robustness of the proposed alternatives under different scenarios. It includes new assumptions, scenario simulation results, and conclusions on the impact of these scenarios on supply chain performance.

Chapter 6 summarises the research findings, discusses the study's contributions, and suggests areas for future research. It also reflects on the current work's limitations and proposes further investigation directions.

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2. Literature Review

This chapter is dedicated to the literature review and description of the fundamental concepts associated with this project to understand the context and research challenges better. The chapter is organised as follows:

Section 2.1 introduces the main concepts regarding SC management and sustainability, which are central to the present dissertation. Then, Section 2.2 presents an overview of multimodal transportation networks, outlining their role and relevance within supply chains. Finally, section 2.3 discusses alternative simulation approaches, analysing current solution options and outlining best practices for performing simulation studies on the impact of multimodal transportation on overall supply chain performance.

2.1. Supply Chain Management

2.1.1. Supply Chain Concepts

A supply chain is a network that encompasses the series of steps and processes involved in the production and distribution of a product. It includes the procurement of raw materials, their transformation into finished goods, and the delivery of these goods to consumers. The chain involves a network of organizations, people, activities, information, and resources, all directed towards efficient and effective product and service provision to the end customer (Carter & Easton, 2011).

The Council of Supply Chain Management Professionals (CSCMP) defined Supply Chain Management (SCM) as the following: "Supply Chain Management encompasses the planning and management of all activities involved in sourcing and procurement, conversion, and all logistics management activities. Importantly, it also includes coordination and collaboration with channel partners, which can be suppliers, intermediaries, third-party service providers, and customers. In essence, supply chain management integrates supply and demand management within and across companies." (*CSCMP SCM*, 2024). Moreover, SCM involves the strategic oversight of sourcing, procurement, and logistics, ensuring active collaboration among all stakeholders, including suppliers and customers, to harmonise supply and demand within and among different companies (*CSCMP SCM*, 2024).

Research aims to identify the most effective solutions for operations management in today's competitive landscape. Supply chains with the best value are more likely to thrive. Best value supply chains prioritise strategic supply chain management to improve speed, quality, cost, and flexibility. While this concept is important for modern organisations, there is limited understanding of how major theories can give light on what sets these chains apart and contributes to their success (Aziz Muysinaliyev, Sherzod Aktamov, 2014)

A comparison between a value chain and a supply chain illustrates their roles from conception to delivery. The value chain is displayed on top, beginning with Customer Requests, emphasising the start of value creation by identifying consumer wants and preferences. This customer-centric approach drives a series of value-adding operations, including designing strategic components and global assembly, culminating in creating the final product (Michael E. Porter, 1985). In contrast, the supply chain begins with 'Product Requests', where the demand for items triggers supply chain activities. The process comprises the complete logistics and distribution trajectory, culminating in fulfilling customer requests via the delivery of final items, hence satisfying the 'Customer' (Michael E. Porter, 1985).

2.1.2.1. Supply Chain Management: Key Concepts and Challenges

Supply chain management has evolved into a complex network of interconnected operations, products, and data streams. Given the rapid pace of globalization and evolving customer demands, supply chains now encounter greater risks and disruptions. Due to this, supply chain resilience has gained attention, highlighting its vital role in allowing supply chains to foresee, adapt to, and quickly recover from these issues. Furthermore, the emphasis on sustainability has expanded beyond economic elements to include social and environmental implications, indicating a more comprehensive approach to supply chain strategy (Longo et al., 2024).

During the thriving decade of the 1990s, industries worldwide faced a watershed moment. They had carefully streamlined manufacturing costs and were now on the verge of a new frontier: Supply Chain Management. They saw the wealth of efficiencies waiting to be unlocked through precise SCM techniques, aided by emerging manufacturing paradigms like just-in-time and lean processes. As the story progressed into the late 1990s, a digital revolution began to spread throughout supply networks. Information and communication technologies promise to solve some of the main challenges in SCM. As these technologies introduced new ways of communication, also new business models emerged based on direct-to-costumer new paradigms (Koberg & Longoni, 2019).

Deregulation in transportation led to various choices and lower costs, but also created logistical complexities. Offshore operations became the norm, scattering industrial activities and intertwining supply chains globally, increasing risks and complexity. On top of this, companies are increasingly held responsible for their operations' and suppliers' sustainable outcomes. In this regard, Sustainable Supply Chain Management (SSCM) has developed over the last twenty years as a method to incorporate environmental, social, and economic objectives into the supply chain practices of a company, aiming to enhance overall sustainability (Koberg & Longoni, 2019).

Sustainable supply chain management integrates environmental and socially responsible strategies throughout the supply chain lifecycle. The challenge of implementing SSCM rises dramatically in global supply chains as organisations must manage diverse legal requirements, cultural norms, and logistical complexities. This integration reduces environmental impacts while maximising social and economic benefits across the supply chain (Koberg & Longoni, 2019).

The inclusion of environmental considerations in SCM literature gave rise to the term "Green Supply Chain Management" (GSCM). GSCM refers to incorporating environmental concerns into all operations of the SC (Payán-Sánchez et al., 2021).

Sarkis et al., 2011, further refines this definition by highlighting the incorporation of environmental concerns into the practices between organisations involved in SCM (Longo et al., 2024). The environmentally oriented practices may include various operational decisions such as selecting suppliers, developing supplier capabilities, choosing modes and carriers for transportation, planning vehicle routes, making location decisions, and selecting packaging options (Carter & Easton, 2011)(Kurnia et al., 2012).

Building on these operational focuses, Samir K. Srivastava, 2007, expands the concept of GSCM to encompass the entire lifecycle of products. He describes it as: “integrating environmental thinking into supply-chain management, including product design, material sourcing and selection, manufacturing processes, delivery of the final product to the consumers as well as end-of-life management of the product after its useful life.” (Srivastava, 2007). This complete approach emphasizes the necessity of taking environmental implications into account during the design process, as well as during disposal and recycling.

In the SSCM field, significant challenges impact the incorporation of sustainable practices within global networks (Seuring & Müller, 2008). These challenges revolve around balancing various sustainability elements, enhancing supply chain resilience, and ensuring compliance with a wide range of regulatory frameworks. The Delphi study facilitates the synthesis of diverse perspectives and extracts underlying themes in a structured manner. In this context, four overarching topics emerged as significant focal points (Seuring & Müller, 2008):

I. Pressures and Incentives for SSCM

The Delphi study highlights the importance of considering customer demand alongside government regulation and NGO pressure in SSCM (Seuring & Müller, 2008). Experts prioritise customer demand for sustainable products, suggesting companies should align practices accordingly. Interestingly, NGOs rank their pressure lower, emphasising the complexity of sustainability challenges.

In contrast, in a case study about corruption in the Brazilian beef supply chain (Silvestre et al., 2018), revealed how it impedes sustainability efforts. This highlights the multifaceted challenges in achieving sustainability, requiring a comprehensive approach that addresses regulatory, stakeholder, and market dynamics.

These findings emphasise the need for comprehensive approaches to sustainable supply chain management, considering various pressures, incentives, and challenges to achieve real progress toward sustainability goals.

II. Identifying and Measuring Impacts on Sustainable Supply Chain Management

Following the findings of the influential Delphi study, the authors underscored the pivotal role of economic viability (Seuring & Müller, 2008). This suggests that economic factors are paramount, as a financially unsustainable supply chain will likely fail, irrespective of its environmental or social merits. Moreover, the scores for the environmental and social dimensions and the integration of all three sustainability dimensions reveal a compact cluster, indicating that these aspects are perceived almost equally in importance. This closeness in scoring, however, was seen as somewhat disappointing because it highlights a lack of distinct prioritisation among the dimensions, suggesting the need for a more nuanced approach in integrating these aspects within supply chain strategies (Seuring & Müller, 2008).

In complement to the Delphi study, Ahi & Searcy, 2015 is an extension of Seuring & Müller, 2008, work promoting the dynamic integration of economic, environmental, and social dimensions within supply chains, emphasising the interdependence of these dimensions and advocating for sustainable supply chains that operate within ecological limits and societal norms.

III. Supplier Management

The study highlights the critical role of including environmental and social criteria in supplier selection, auditing, and monitoring, reflecting industry trends towards responsible supply chains. Certification of suppliers according to sustainability standards is also recognized as beneficial (Seuring & Müller, 2008).

Managing suppliers comprehensively presents significant challenges but is crucial for ensuring long-term sustainability and ethical compliance in supply chain operations (Sheth & Sharma, 1997). This approach responds to regulatory pressures and aligns with the increasing consumer demand for transparency and corporate responsibility, highlighting the importance of integrating sustainable practices at every level of supply chain management.

IV. Supply Chain Management

This topic delves into more than just the individual supplier-customer interface; it focuses on the entire supply chain. It highlights the importance of 'cooperation and communication between supply chain members,' fostering a proactive approach to managing operations. Following closely is the emphasis on 'risk management across the supply chain,' which aims to discover environmental and social issues before they become public and could undermine the company's brand reputation.

Complementing these efforts is the consideration of the 'total life-cycle of the product,' which is critical for guaranteeing strong environmental and social performance (Seuring & Müller, 2008). Furthermore, a shared viewpoint on achieving sustainability and improving sustainable supply chain management through learning and innovation is considered crucial, albeit less so. However, even the least crucial concerns are relevant, demonstrating that all components found and refined through content analysis are critical for long-term supply chain management. This shows that addressing sustainability challenges in supply chains requires a comprehensive and integrated approach (Seuring & Müller, 2008).

Numerous studies underscore the significant challenges of integrating Sustainable Supply Chain Management (SSCM) into global frameworks, noting the difficulties across varied legislative, cultural, and economic environments (Koberg & Longoni, 2019; Longo et al., 2024; Seuring & Müller, 2008). These challenges are particularly pronounced in multi-tier supply chains, which require direct supervision and robust linkages to ensure sustainability (Koberg & Longoni, 2019). Addressing these issues demands a comprehensive approach that combines modern technical tools, strategic management techniques, and extensive collaboration across all levels of the supply chain to integrate sustainability practices worldwide effectively.

2.1.3. Performance measures in SC

In contemporary supply chain management, establishing robust performance measurements is vital for assessing the effectiveness and efficiency of existing systems and guiding the development of new systems (Beamon, 1998). These performance measures can be broadly classified into qualitative and quantitative categories, each serving distinct but complementary roles in supply chain analysis as proposed by Beamon, 1998.

- Qualitative Performance Measures: These measures, which include customer satisfaction, flexibility, information and material flow integration, effective risk management, and supplier performance, are crucial for assessing the more intangible aspects of supply chain operations. Although not directly quantifiable, these measures provide insights into the qualitative improvements within a supply.
- Quantitative Performance Measures: On the other hand, quantitative measures offer a numerical evaluation of a supply chain's performance. They can be further divided into two main types: (1) those focused on financial objectives such as cost minimization, sales maximization, and return on investment; (2) those aimed at customer responsiveness, like minimizing lead times, customer response time, and product lateness.

Recent research has continued to explore these dimensions, emphasizing the need for resilience and strategic flexibility within supply chain systems, particularly in the face of global disruptions such as pandemics and supply chain interruptions (Gaudenzi et al., 2023).

2.1.4. Decision support tools in SCM

In the context of SCM, decision support tools are critical for making effective and efficient operational and strategic decisions. The strategic aspects of SCM are significantly enhanced by decision support tools, as they provide frameworks for measuring performance and aligning supply chain operations with broader business objectives. Beamon, 1998, provides a foundational perspective on this, stressing the importance of performance measurements in evaluating the effectiveness of supply chain operations.

The importance of these tools has grown in recent literature, stressing their diverse contributions to SCM (Ivanov et al., 2017; Wartha et al., 2002). Simulation models can improve predictive skills in supply chains, resulting in better risk management and operational planning (Taticchi et al., 2015). The authors Taticchi et al., 2015, describe tools that use advanced modelling approaches to foresee and prevent probable supply chain interruptions, allowing for more proactive decision-making. These competencies are critical, especially in managing the intricacies of modern supply chains prone to numerous worldwide disturbances. Ivanov et al., 2017 extend this by investigating the optimisation of production planning in manufacturing systems, emphasising the importance of decision support systems in managing complex industrial environments and global supply chains.

Modern decision support technologies also consider sustainability and environmental effects, which are becoming increasingly important in global supply chain operations, as mentioned in chapter 2.1.2.1**.** Sustainable supply chain management in emerging markets stresses the significance of decision support systems in supporting ecologically friendly practices, demonstrating how these tools assist enterprises to fulfil both efficiency and ecological goals (Tian et al., 2023).

As SCM evolves, decision support technologies must adapt to a more complex and interconnected global market. The continuous integration of AI and machine learning into these technologies points to a future in which supply chain choices are more data-driven, predictive, and responsive to changing global conditions.

2.2. Multimodal Transport Networks

2.2.1. Overview of Multimodal Transport Networks

Multimodal transportation is a relatively recent subject characterised by diverse definitions. According to Dua & Sinha, 2016: “The concept of multimodal transportation can be described as the movement of freight with more than two different modes, and it is known at the end consumer address in current transportation process is decided”.

Research in logistics predominantly focuses on transportation, typically examining single-mode systems or their integration into manufacturing processes (Agamez-Arias & Moyano-Fuentes, 2017). Interest in multimodal freight transport emerged in the 1990s, initially concentrating on specific issues, such as planning and opportunity costs (Bontekoning et al., 2004). Over time, studies expanded to include diverse transportation modes, policy analysis (Turcksin et al., 2011), and regional planning studies (Mathisen & Hanssen, 2014). Since then, there has been a steady increase in papers studying the subject, originating new and innovative ideas (Agamez-Arias & Moyano-Fuentes, 2017). Moreover, the rise of global commerce has also contributed to boost an increased interest in multimodal transportation due to its cost-effectiveness and efficiency benefits, showing a 20% reduction in transport costs over unimodal systems and optimal efficiency at a 63% train loading capacity (Kordnejad, 2014). Additionally, this transportation mode has gained attention for its lower environmental impacts, potentially reducing CO_2 emissions by 57% compared to traditional road transport, further highlighting its growing significance in both economic and ecological research spheres (Agamez-Arias & Moyano-Fuentes, 2017).

2.2.2. Multimodal Transportation Solutions

Multimodal transportation solutions combine several means of transportation—such as road, rail, sea, and air—to improve the efficiency and environmental sustainability of logistical operations. This strategic approach takes advantage of each mode of transportation's distinct characteristics to reduce overall environmental impact while increasing supply chain flexibility.

- Rail Transport: Rail transport is highly regarded for its remarkable efficiency and environmental friendliness, making it ideal for long-distance delivery of bulk commodities. According to Sun et al. (Sun et al., 2015), trains can transport a ton of freight up to four times farther on a gallon of gasoline than trucks, resulting in significant energy savings and emissions (Liao et al., 2009). Furthermore, railroads alleviate traffic congestion and pollutants by transporting significant amounts of freight off public highways. Rail transit is inflexible due to fixed lines and rigorous scheduling, making it difficult to adjust to changing logistics demands and requiring significant initial infrastructure investment (Sun et al., 2015).
- Maritime Transport: Maritime transport plays a significant role in international logistics because of its low cost and substantial capacity to transfer large volumes over vast distances. It is known for its energy economy, as it consumes much less fuel per ton-mile than other modes of transportation such as air or road. This mode of transportation is particularly beneficial in terms of lowering overall transport emissions, making it an essential component of sustainable logistics plans. According to Christiansen et al., 2007, maritime transport plays an important role in global supply chains by providing a dependable and flexible option that can react to seasonal swings and market demands without the need for substantial infrastructure investments associated with other modes. However, the fundamental drawback of maritime transport is its relatively slower pace, which can result in prolonged transit times. This makes it less suitable for time-sensitive shipments, unless it is strategically paired with faster transport modes such as air or road for parts of the logistics chain where speed is crucial. Additionally, maritime transport can be affected by geopolitical and environmental factors that may influence shipping routes and schedules, adding a layer of complexity to logistics planning (Christiansen et al., 2007).
- Air Transport: This means of transport is critical for quickly transporting high-value, time-sensitive commodities over long distances. It offers the fastest delivery times available, which is critical for perishable commodities or urgent shipments (Christiansen et al., 2007). However, it is the most energy-intensive mode of transportation, with high fuel consumption and carbon emissions per ton-mile compared to other modes (Feng et al., 2023). Despite its speed, the operational

expenses and environmental impact render it unsuitable for less urgent or large cargo. Integrating air with other modes of transportation, such as sea or rail, can improve efficiency and sustainability, providing a balanced solution to current logistical concern.

- Road Transport: Road transport is a key component of contemporary logistics, providing unmatched flexibility and critical last-mile delivery capabilities. Its capacity to instantly adjust to changes in delivery schedules and routes makes it ideal for providing door-to-door service and filling gaps caused by other modes of transportation. Road transport's versatility makes it suitable for a variety of logistical needs, including urban delivery and rural access (Powell et al., 2007, p. 5). Despite its advantages, road transport has relatively high emissions and fuel consumption per ton-mile. The environmental impact is significant, contributing to urban air quality issues and noise pollution (Liao et al., 2009). However, advances such as electric and hybrid vehicles are beginning to offset these consequences and promote a cleaner pathway for road transport. Integrating road transport with rail or maritime solutions allows logistical operations to strike a balance between speed, cost-efficiency, and environmental sustainability, improving the overall effectiveness of the supply chain.

The appropriate management and integration of several types of transportation into a multimodal approach can considerably improve logistical efficiency and sustainability. For example, using rail for most of a freight journey and road transport for local distribution can improve energy efficiency and reduce emissions. Similarly, merging air transport for urgent deliveries and sea freight for regular, bulk products can efficiently balance speed and cost (Sun et al., 2015).

2.2.3. Challenges and Barriers in Multimodal Transport Networks

Multimodal transport networks, which combine several modes, seek to improve the efficiency and sustainability of transportation systems. Despite their potential, numerous hurdles limit their integration and operational efficacy.

According to Agamez et al., 2017, social equity issues and the balance of cost-efficiency are significant concerns, as transportation plans frequently fail to uniformly benefit all segments of society.

Additionally, Feng et al., 2023, highlight that challenges like bridge height restrictions can significantly disrupt transportation flow in networks involving inland waterways, requiring detailed modeling and strategic planning to optimize routes and modes. Both studies suggest that an integrated approach that includes advanced modeling techniques and considers unique environmental and infrastructural factors is crucial for overcoming these barriers.

Improvements might involve developing more comprehensive policies that reflect the diverse needs of multimodal networks, as well as improving coordination among different forms of transportation. As demonstrated by Feng et al., 2023, leveraging technologies such as containerization can play a critical role in boosting the efficiency of multimodal networks and lowering operational expenses. As suggested in the paper, it's argued that adopting such technologies, together with strong legislative backing, can greatly reduce the economic and logistical constraints of multimodal transportation. By solving these difficulties, multimodal transportation may reach its full potential as a foundation for sustainable and efficient logistics.

2.2.4. Multimodal Transport Networks and Sustainable SC Management

Sustainable transportation within supply chains aims to reduce the environmental impact of logistics activities while maintaining economic viability and social equality. The aim of sustainable transportation is to promote modes and practices that minimize energy consumption and pollution while remaining efficient and safe for both people and products (Mihyeon Jeon & Amekudzi, 2005). This requires a change away from old practices and toward creative strategies that take into account the long-term health of the environment and society (Kennedy et al., 2005).

A critical component of sustainable transportation is the adoption of green logistics, which integrates advanced logistical procedures and technologies to reduce greenhouse gas emissions and other pollutants. For example, deploying vehicles powered by alternative fuels such as electricity, hydrogen, or biofuels significantly lowers the carbon footprint of transportation networks (Kennedy et al., 2005). These vehicles release fewer pollutants than traditional gasoline or diesel engines, making a significant contribution to improving air quality and lowering the sector's overall carbon footprint.

Furthermore, sustainable transportation practices encompass how logistics are carried out across the supply chain by integrating multimodal transport solutions. This strategy incorporates a variety of transportation modes, including rail, ship, and truck, each chosen for its unique characteristics. Railways are extremely energy-efficient and perfect for long-distance bulk transport, whilst ships provide a low-carbon choice for international freight. Trucks give critical flexibility for last-mile delivery and access to remote locations. Together, these modes reduce dependency on energy-intensive options, hence improving transportation sustainability and efficiency (Leuenberger et al., 2014). Sophisticated management systems optimize these modal changes, resulting in seamless and efficient freight transportation across the supply chain (May & Crass, 2007).

However, implementing sustainable transportation faces several challenges. High initial costs for new technologies, resistance to change within the logistics sector, and inadequate infrastructure for alternative fuels are significant barriers. Legislative support and incentives are crucial to fostering the widespread adoption of sustainable practices (Leuenberger et al., 2014).

As the demand for sustainable transportation grows, it is imperative for companies and governments to invest in and promote methods that reduce environmental impact, improve economic efficiency, and enhance societal well-being (May & Crass, 2007). The transition of transportation logistics toward sustainability is not merely a trend but a necessary response to the escalating challenges of global trade and environmental conservation.

This dissertation aims to address these challenges by optimizing the integration of multimodal transport solutions through decision support systems, enhancing supply chain resilience and sustainability.

2.3. Simulation

2.3.1. Simulation as a tool for decision support systems

Simulation is becoming increasingly important in decision support systems, allowing for the modelling of complicated situations to understand better and enhance supply chain (SC) operations (Terzi & Cavalieri, 2004). It allows you to visualise complex constraints and system behaviours over time, improving comprehension and managing varied scenarios.

Simulations allow for testing various network topologies under several conditions to understand systems' behaviour and operational dynamics. This approach enables strategic planning without the disruptions that real-world testing may cause, providing a cost-effective and efficient alternative (Law, 2022).

A simulation model of a complex system is always an approximation of the real system no matter how much effort is spent on model development. Absolute model validity does not exist, and is not even desirable (Law, 2022). After all, a model is supposed to abstract and simplify reality. A simulation model should be designed considering the specific features and objectives of the system in analysis, and with a clear plan for conducting the simulation study. According to Law, 2022, a seven-step approach should be followed to conduct a successful simulation study.

The first step is to **formulate the problem**. This step requires a detailed description of the problem, the establishment of the study's main objectives, the identification of specific questions to be addressed, the definition of performance measures for evaluating various system configurations, the determination of which system configurations to model, and the study's time frame (Law, 2022). The following stage is **gathering information** about the system's structure and operational practices and creating an assumptions document.

Once the **assumptions document has been validated**, **model programming** can begin with a commercial simulation software package (such as AnyLogic, Arena, ExtendSim, FlexSim, Simio, SIMUL8, and so on) or a general-purpose programming language like C++ or Java.

The next phase is **model validation**, which involves verifying the accuracy of the simulation by comparing its output with real system data, if accessible. A sensitivity analysis should be conducted to determine which factors significantly impact the performance metrics and hence require rigorous modelling (Law, 2022).

The last steps include **conducting experiments** for each system configuration of interest, **collecting data, and thoroughly documenting the findings**. The assumptions document, a detailed computer program description, and the present research results are all necessary components of the documentation. To increase the model's credibility, the simulation study's final presentation should contain an animation and an explanation of the model development and validation methods (Law, 2022).

2.3.2. Simulation approaches

Various simulation techniques can be employed to model a system, including Discrete Event Simulation (DES), System Dynamics (SD), and Agent-Based Modeling (ABM), each offering distinct approaches and benefits.

DES has long served as a cornerstone in Operational Research simulations, providing a process-oriented method that meticulously details the system to analyse its behaviour. This technique is particularly effective for scenarios that involve queues, where the processes are clearly defined, making it ideal for operational or tactical level modelling (Owen et al., 2010). In contrast, SD offers a broader perspective by modelling the system through continuous state changes over time using stocks and flows, making it well-suited for addressing problems at a strategic level (Owen et al., 2010).

ABM, on the other hand, focuses on individual entities and their interactions within the system. This technique does not incorporate queues or flows but emphasizes the autonomous actions and operations of the modelled entities, providing a unique approach to understanding complex dynamics (Owen et al., 2010).

Table 2.1: Comparison of Simulation Approaches – Simulation Modeling and Analysis (Law, 2007)

Approach	Key Features	Applications in SCM	Advantages	Limitation
Discrete Event Simulation (DES)	Models' system as a sequence of discrete events	Production lines, inventory systems, logistics operations	Detailed analysis of system dynamics, bottleneck identification	Requires detailed event data, can be complex to model
System Dynamics (SD)	Uses differential equations, focuses on interactions and feedback loops	High-level strategic modeling, policy impact analysis	Long-term impact analysis, handles feedback loops well	Less detailed than DES, may oversimplify complex systems
Agent-Based Modelling (ABM)	Simulates actions and interactions of autonomous agents	Consumer behavior, market dynamics, network effects	Models' complex adaptive systems, captures emergent behaviors	Computationally intensive, requires detailed agent rules

2.3.3. Case studies implementing simulations

Recent research demonstrates substantial advances in the use of simulation in supply chain management, notably in terms of resilience and sustainability.

In 2010, Owen et al., (2010) conducted research examining the critical significance of labor stability and diversified sourcing. The study delves into how operational flexibility and strategic risk management are interconnected, resulting in a complex framework supporting supply chain sustainability in various scenarios. Christopher and Holweg, 2011, in their work highlighted the importance of efficient transportation networks in maintaining supply chain resilience during disruptions. Their research underscores the need for rapid and flexible transportation options to mitigate the impact of unforeseen events on supply chains (Christopher & Holweg, 2011).

Following this, Ivanov et al., 2017, created a model incorporating disruption risks into supply chain architecture, allowing for evaluating resilience methods such as using numerous suppliers to reduce risk. This model facilitates the assessment of various resilience approaches, particularly supplier diversification as a risk mitigation tool, demonstrating its usefulness in improving supply chain robustness against unforeseen disruptions.

Mönch et al., 2018, further explored the effects of sustainable practices on SC performance amid disruptions. Their study underscored the importance of proactive inventory management and resilient sourcing techniques in ensuring SC performance during unanticipated circumstances. This research discusses the broader implications of such methods for sustainable development within supply chains (Mönch et al., 2018).

These studies emphasise the importance of integrating resilience and sustainability within SC management. They argue that strategic use of numerous suppliers, inventory reduction, and increased operational flexibility are critical for avoiding future disruptions and promoting sustainable practices throughout supply chains.

Given the challenges in supply chain management, particularly in multimodal transportation contexts, this dissertation aims to address these issues by developing simulation models that enhance resilience and sustainability in supply chains. The focus will be the development of a decision support system based on simulation methods to optimise transportation modes within the SCM context to manage uncertainty and sustainable supply chain operations effectively.

2.4. Conclusion

In this chapter, it was examined the literature on multimodal transportation and supply chain resilience, emphasizing important gaps in real-time data analytics and multimodal transport integration. Even with an abundance of supply chain management studies, much is still overlooked regarding the dynamic character of contemporary supply chains—a critical aspect of managing the complexity and unpredictability of the global market.

This dissertation's main goal is to fill in these gaps by creating a thorough simulation model that uses various simulation approaches. This model seeks to represent the dynamic interactions that occur throughout supply chains. In doing so, the study aims to improve our comprehension of how multimodal transport solutions might support the resilience and efficiency of supply chains.

To conclude, this chapter emphasizes the need of an integrated approach to multimodal transport and real-time data analytics to increase supply chain resilience and efficiency, laying the groundwork for the simulation model's future development and use. By filling in the gaps, this dissertation seeks to develop supply chain management both theoretically and practically.

3. The Problem and Methodological Approach

As previously mentioned, this work aims to build a simulation-based platform to test the effectiveness and sustainability of intermodal transportation routes across the supply chain and assess its performance under different scenarios and conditions.

3.1. Context and General Problem

To accomplish the main goals defined in this project, various multimodal strategies will be explored to assess their contributions to the overall SC sustainable performance in uncertain environments. By subjecting the overall SC network to uncertain scenarios, the various multimodal system's primary weaknesses should become apparent, allowing for the investigation of the most suitable transportation network designs towards more sustainable and resilient SC operations

In this regard, this dissertation provides a simulation model for describing, testing, and evaluating the behaviour of a global SC, considering different intermodal transportation network designs. This model identifies and addresses risks by employing various strategic measures, such as modifying routes and modes of transportation or adapting facility inventory and capacity. This strategic approach attempts to improve the supply chain's sustainability, resilience and efficiency, ensuring it can cope with potential disruptions.

As the purpose of this dissertation is to provide a platform capable of optimizing multimodal transportation routes for any generic supply chain, a general representation of such a supply chain is required. This supply chain, which focuses on intermodal transportation, will include suppliers, ports, logistic platforms for transshipment operations, distribution centers (DCs), and customers. Figure 3.1 shows a simplified illustration of the generic multimodal transportation supply chain.

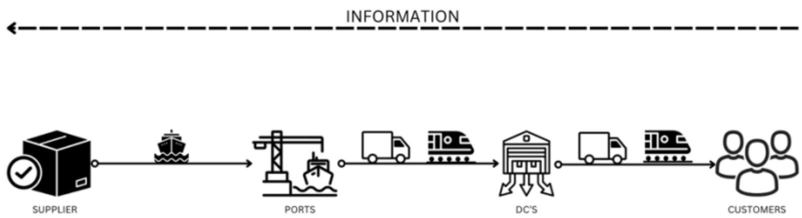

Figure 3.1: Generic Supply Chain

This figure depicts the important elements and flows of goods from the initial suppliers through different transportation modes (including boat, truck and train) to the final delivery to customers.

According to Law, 2022, **Customers** play a crucial part because they are the final recipients of the products. To meet their needs efficiently, these clients rely on the inventory management system handled by the DCs. On their turn, the **distribution centers** must have the necessary stock on hand to fulfill orders quickly. In this generic SC, the distribution centers, acquire inventory by placing orders to the suppliers that use maritime transportations and ports infrastructures to fulfill the DCs purchasing orders. Thus, in this case study, the ports serve as key intermediaries in which the orders are aggregated and consolidated before the delivery to the DCs (Law, 2022).

This configuration is intended to handle large volumes of goods, reflecting the complexities of managing worldwide shipments and local distributors. **Ports** constitute vital nodes for receiving and shipping goods to distribution centers, connecting different transportation modes. They manage products sourced via multiple international suppliers and coordinate logistics for the hinterland to the various distribution centers. This system ensures that items are distributed efficiently across the network, with a constant flow to meet the changing needs of end users (Law, 2022).

Finally, the **suppliers** are responsible for producing and delivering the products to the ports. They are essential for producing the required quantities and ensuring the supply chain's integrity and responsiveness to market demands (Law, 2022).

In an ideal scenario, this generic supply chain should respond to all customer demands, adapt to demand changes, and be resilient to disruptive events such as economic downturns or logistical interruptions. However, events like the COVID-19 pandemic have demonstrated that these principles are difficult to accomplish, emphasising the importance of building proactive measures and rigorous preparation for unexpected events.

3.2. Problem Conceptualization

Following the methodology based on Law, 2022, building a realistic and coherent model starts by documenting all the case study structural and behavioural requirements and features, identifying the entities, and describing the simplifications and assumptions to be made.

In this regard, a generic supply chain will be considered to validate and demonstrate the applicability of the proposed decision-support system. As the main goal of this work is to explore the potential benefits of multimodal transportation strategies, a generic SC was defined considering the geographic region of the Iberian Peninsula and exploring the connections provided by the Atlantic Rail Freight Corridor (ARFC) (https://www.adif.es/en/sobre-adif/red-ferroviaria/corredores-transeuropeos).

It is essential to understand the broader European transportation network to highlight the importance of multimodal transport within the context of the Iberian Peninsula. The Trans-European Network - Transport initiative, specifically the Core Network Corridors, is critical in promoting European connectivity. These corridors encompass railways, roads, airports, ports, and maritime routes, linking major communication nodes and facilitating efficient and sustainable transport. The following Figure 3.2 illustrates this same network of corridors, with particular emphasis on those passing through Spain, namely the Mediterranean and the Atlantic corridors.

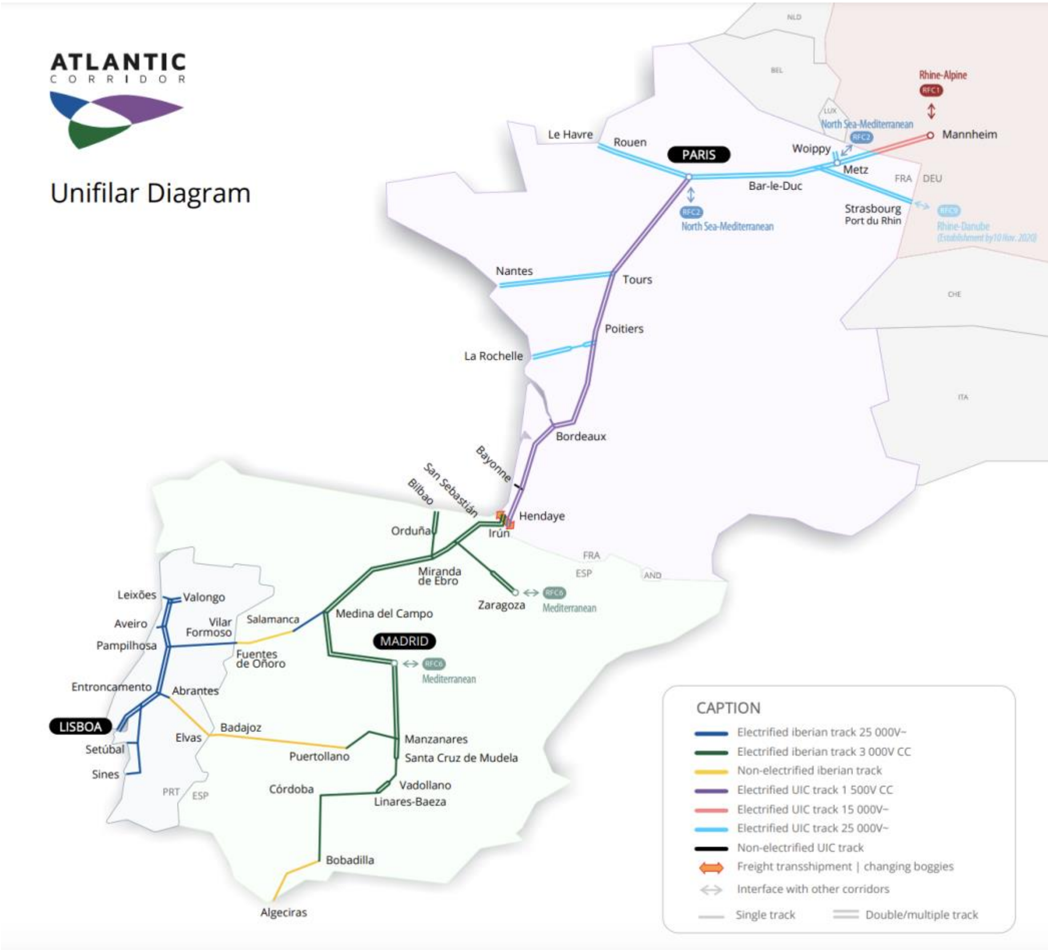

Figure 3.2: Atlantic Rail Freight Corridor - https://www.adif.es/en/sobre-adif/red-ferroviaria/corredores-transeuropeos

Therefore, considering the main entities described earlier in Section 0, each of these entities has its own features, requirements, and operating modes, as follows:

- Suppliers - These entities represent the origin point for goods entering the supply chain and accommodate the following features:
    - Geographic location with coordinates reflecting strategic placement near major transportation hubs or ports;
    - Located in regions beneficial for logistics, such as areas with lower labour costs or proximity to major ports: Hong Kong, Asia, and Georgia in America;
    - Limited to two locations to streamline logistics and minimise complexity;
    - Defined production capacities;
    - Integrated order management systems to handle requests from DCs efficiently, using ports as intermediaries;
    - Limited inventory capacity but with options to expand as needed;
    - Pre-determined transportation arrangements to send goods to ports.

- Ports - Key transit points for goods entering the multimodal transportation network with the following features:
  - Specific geographic locations, distributed strategically along the ARFC to facilitate inbound and outbound logistics and multimodal strategies;
  - Handle multiple product lines, receiving goods from suppliers and consolidating them to be shipped to the distribution centers;
  - Maximum throughput and storage capacities with variable cost structures;
  - Order management systems to synchronize with DC requirements;
  - Capabilities for scalability in operations and storage;
  - Limited but efficient transportation setups to distribute goods to subsequent network nodes (DCs) in the hinterland.
- Logistic Platforms - Standby points for rail transportation, acting as intermediaries between ports and distribution centers with the following features:
  - Be Located strategically across the Iberian Peninsula region to optimize logistics routes between ports and DCs;
  - Serve as key nodes for handling final product assortments before distribution to DCs;
  - Equipped with advanced inventory and order management systems designed to manage goods in transit efficiently;
  - Limited but scalable storage facilities;
  - Integrated transport systems to coordinate and manage the transfer of goods between ports and distribution centers.
- Distribution Centers (DCs) - Key intermediaries ensuring goods are processed and delivered to customers. The following features are considered:
  - Located strategically across the Iberian Peninsula region to optimize logistics routes
  - Larger in number than suppliers to ensure proximity to end customers;
  - Handle final product assortments and prepare for direct distribution;
  - Inventory and order management systems defined to meet swiftly to customer demands;
  - Limited but scalable storage facilities;
  - Integrated transport systems to manage and execute delivery to customers.
- Customers - The final recipients in the supply chain, crucial for the demand-driven logistics model. Characteristics include:
  - Specific geographic locations often in urban centers to maximize coverage.
  - Directly receive goods from DCs, requiring precise and timely delivery mechanisms.
  - Limited inventory capacity, requiring efficient replenishment systems.

- Capability to adjust storage and ordering strategies based on demand fluctuations.

Moreover, the flow of information going upstream in the supply chain triggers the flow of products downstream. Hence, two critical entities also need to be defined, namely:

- Orders – this entity represents informational transactions between the supply chain elements, functioning as inventory requests. An order is created every time a facility requests products from upstream supply chain. These orders should detail:
  - The origin (facility) of the order;
  - The destination (facility) of the order;
  - The quantity of the product to be sent;
- Product - Physical products moving down the supply chain according to customer needs. Each product entity is defined by the product type, dispatch time, and its volume measured in cubic meters (m^3).

Given the focus on exploring multimodal transportation networks under uncertainty, some additional requirements for the simulation model in this dissertation are defined as follows:

- Simulation Horizon: To efficiently capture the SC dynamics and the performance of long-term strategies under different conditions, it is considered a simulation horizon of 1 year;
- Customisable Supply Chain Model: The model is general enough to be adapted to different multimodal transportation configurations and business contexts;
- Configurable Logistics Parameters: Transportation times, costs, and capacities at different nodes (ports, DCs, locations, and product demand profiles are easily parameterisable;
- Ease of Introducing Disruptions: The model can easily integrate potential disruptions (e.g., strikes, natural disasters, economic shocks) to test the supply chain resilience;
- Comprehensive KPIs: Performance evaluation through robust Key Performance Indicators, including demand satisfaction, carbon dioxide production, lead times, and overall costs;
- Failure Identification: The simulation model enables the identification of the most vulnerable elements within the supply chain to facilitate targeted improvements.

Additionally, given the significant complexities of the multimodal transportation network, a set of assumptions and simplifications needed to be made, as follows:

- Operational Independence of Distribution Centers: Distribution centers operate with multiple logistics lines where each line handles a specific transportation process. Each logistics line has its own independent resources and can operate concurrently without interference (logistics lines are assumed to be independent);
- Negligence of Setup Times: Given the long-time horizon considered for the simulation, setup times in distribution facilities are ignored as they will not significantly impact the simulation results;
- Uniform Transportation Costs: It is assumed uniform transportation costs per unit distance across similar modes of transport to simplify cost calculations;

- Variable Lead Times: Assume lead times for transportation follow a normal distribution, accounting for variability due to conditions such as traffic or weather;
- Queue Management: When there are queues in the process, processing will follow a First In, First Out (FIFO) approach;
- Full Truck Load (FTL) Operations: The model assumes FTL standards, requiring a minimum cargo load per shipment, depending on the transportation mode. This policy guarantees that transport capacity is optimally utilized while preventing underloading and increasing cost efficiency;
- Simplified Inventory Policies: A single inventory policy (e.g., reorder point) across all distribution centers is considered;
- Order Fulfillment Guarantees: When an order is made, there is no time limit for that order to arrive, and no order cancellations are considered, whether for suppliers, ports, or distribution centers;
- Immediate Demand Fulfillment: Product demand at customer endpoints needs to be immediately met, or it is considered to be lost (there is no waiting for stock at customer locations).

These assumptions simplify the complexities of modeling such a complex multimodal transportation network. They allow the DSS to optimise high-level multimodal strategies, thus enhancing the model’s utility and strategic relevance in real-world applications.

3.3. Simulation Model

Considering the main components associated with the current problem, namely: (i) the requirements, assumptions, and simplifications of the case study, (ii) the issues in the SC that are meant to be identified, (iii) the types of decisions that must be taken, and (iv) the simulation paradigms reviewed in Section 2.3.2 and their specific characteristics, it was decided to use the AnyLogistix software as described below in the next section.

3.3.1. Simulation Software

Given the requirements for this dissertation, including the need for a comprehensive and flexible simulation tool that can handle complex multimodal transportation networks, AnyLogistix was selected as the best simulation software.

AnyLogistix is a comprehensive simulation software tailored for supply chain and logistics analysis. It supports various simulation paradigms, including discrete event simulation, agent-based modeling, and system dynamics. The software's robust capabilities in Greenfield Analysis, Network Optimization, and detailed simulation make it an ideal tool for enhancing the efficiency of multimodal transport networks.

The AnyLogistix simulations provide insights into supply chain vulnerabilities. By assessing multiple scenarios, the model provides valuable insights for optimizing routes, adjusting inventory levels, and enhancing overall supply chain robustness.

Therefore, this dissertation seeks to create a simulation model to examine several multimodal tactics under different scenarios and alternatives, using the software's simulation capabilities.

3.3.2. Configuration and Execution of the Simulation

The supply chain configuration is a critical step performed at the simulation startup. This process uses a Configuration Excel File containing the model's main input parameters. Different supply chain configurations can be tested and evaluated by adjusting these parameters. Some of the most relevant and used tables are:

- Demand: Data on product demand across different regions and customer groups;
- Distribution Centers (DCs) and Factories: Information about the locations, capacities, and operations of DCs and manufacturing facilities;
- Loading and Unloading Gates: Specifications of the gates used for logistics operations at logistic platforms;
- Inventory: Information about stock levels, replenishment cycles, and storage capacities;
- Locations: Geographic coordinates and details of all supply chain nodes, including suppliers, ports, logistic platforms, DCs, and customers;
- Paths: Routes and transportation links between supply chain nodes;
- Shipping: Details about the shipping methods and schedules, including transportation modes and carrier information;
- Sourcing: Information on the sources of raw materials and products, including supplier details and procurement strategies;
- Transportation Modes: Specifications of the different transportation methods used in the supply chain, such as trucks, trains, ships, and planes. This includes their capacities, costs, and transit times;

As demonstrated in Figure 3.3, these tables enable precise control over the simulation setup. Different supply chain configurations can be tested and evaluated by adjusting these parameters. This flexibility allows for the simulation of various scenarios, including normal operations, disruptions, and recovery strategies.

The Configuration Excel File also facilitates the introduction of disruptive scenarios. Modifying specific variables can simulate the impact of disruptions such as natural disasters, economic downturns, or supply chain bottlenecks. Additionally, this setup allows for implementing and testing mitigation measures, providing insights into the resilience and robustness of the supply chain under various conditions.

Continuous validation and adjustments of these parameters are essential to ensure the simulation accurately reflects real-world dynamics. The use of a well-structured configuration file streamlines the process, making it easier to adapt to new information or changing circumstances.

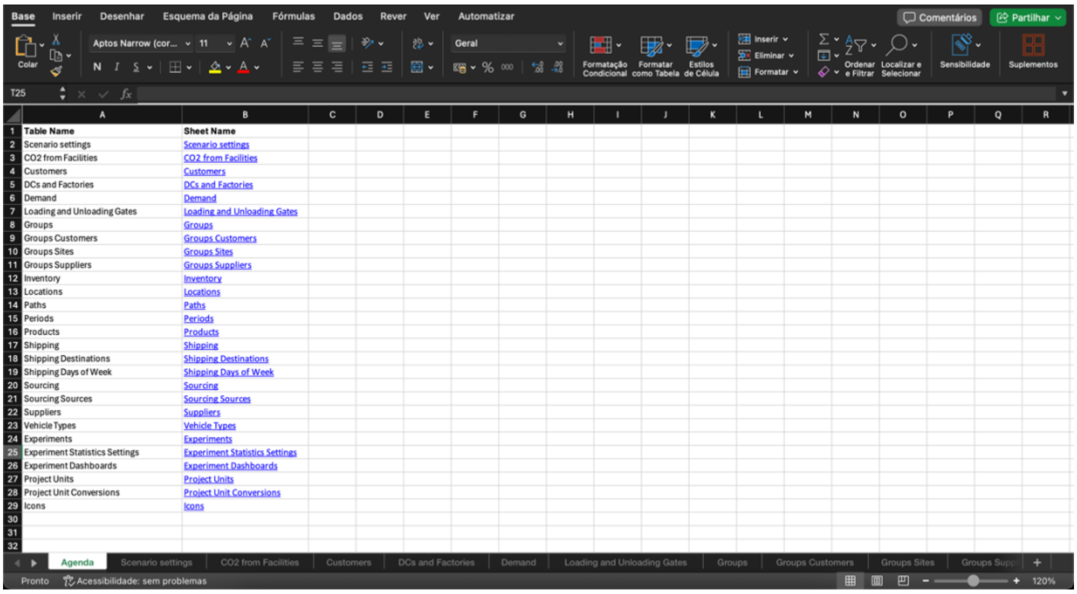

Figure 3.3: Example of an Excel Configuration file

3.3.3. SC Performance Evaluation

Overall supply chain performance can be visualized using various dashboards and tables in the Statistics Dashboard tab of the simulation, as depicted in Figure 3.4.

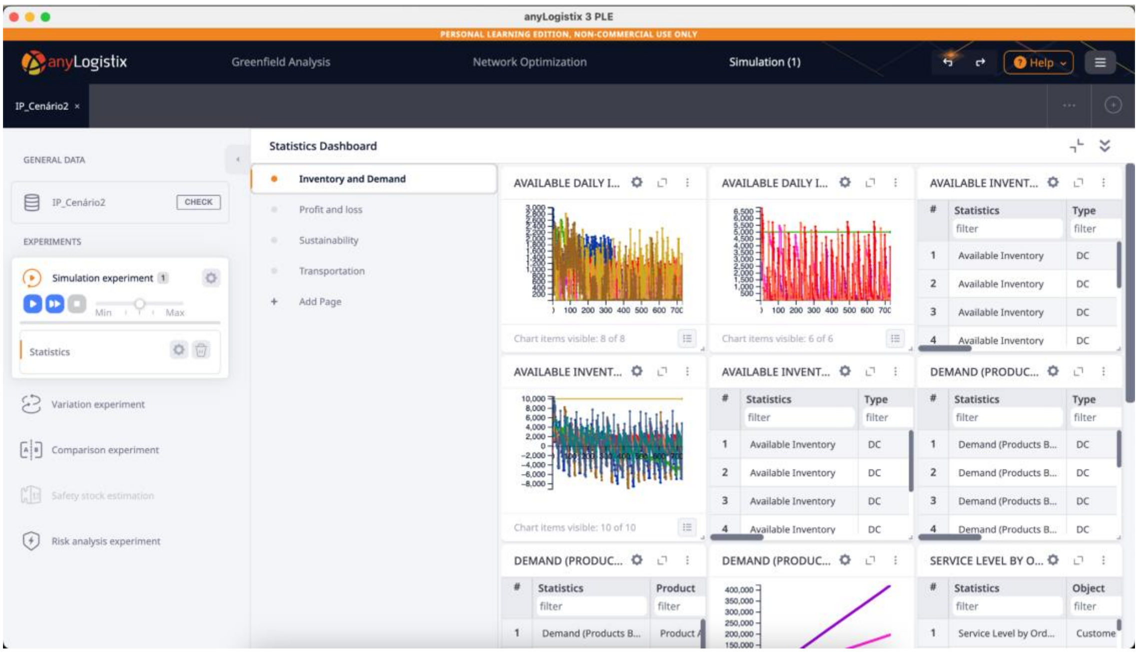

Figure 3.4: Statistics Dashboard in AnyLogistix

The results from these simulation experiments can be exported to an Excel file for further analysis, facilitating deeper insights and a more detailed evaluation of the supply chain performance.

These four tabs offer a full view of supply chain performance. The extensive dashboards provide stakeholders with a thorough insight into supply chain dynamics, allowing them to discover areas for optimisation and development.

I. Inventory and Demand

This tab provides specific information on the available daily inventory at ports and distribution centers. It provides charts that show how inventory levels fluctuate over time. Performance parameters such as available inventory, backlog, and demand fulfillment are shown. These measurements help evaluate how successfully the supply chain satisfies consumer demand and controls stock levels.

Additionally, this tab shows the service levels of the customers and products, providing critical insights into how effectively the supply chain is meeting service requirements.

II. Profit & Loss:

This tab allows you to evaluate financial performance by tracking expenses, revenues, and overall profitability of supply chain operations.

This section's metrics include cost breakdowns for production, transportation, and inventory holding, giving a complete picture of the supply chain's financial health, are represented in RMU (Relative Measurement Unit).

III. Sustainability:

The sustainability tab highlights the environmental impact of supply chain activity. It includes data on CO2 emissions from various facilities and transportation operations. This tab aids in determining the sustainability of supply chain activities and finding areas for improvement to reduce environmental impact.

IV. Transportation:

This category gives specific information about transportation activities, such as shipping routes, vehicle types, and travel times.

This section's key performance indicators include transportation costs, lead times, and order and location-specific service levels.

3.4. Case Study

The case study of this dissertation is inspired by the extensive multimodal transport connections within the Iberian Peninsula. It considers key maritime and rail networks, including the strategic importance of the Port of Sines and the integrated rail infrastructure outlined by the *Administração dos Portos de Sines e do Algarve* (APS) and *Administrador de Infraestruturas Ferroviarias* (Adif). These connections facilitate seamless transitions between transportation modes, enhancing the overall logistics network. By leveraging these well-established routes, the study aims to demonstrate how efficient multimodal transport can significantly improve supply chain performance across the region selected for this case study.

The simulation model replicates the dynamics of a multimodal transportation network, focusing on the Iberian Peninsula and its global connections. Figure 3.5 details the case study within the Iberian Peninsula, highlighting key nodes such as suppliers, ports, logistic platforms, and distribution centers.

Figure 3.6 expands the scope to global supply chain connections, including major international suppliers. These visual representations form the foundation for evaluating multimodal transportation strategies and their impact on supply chain performance.

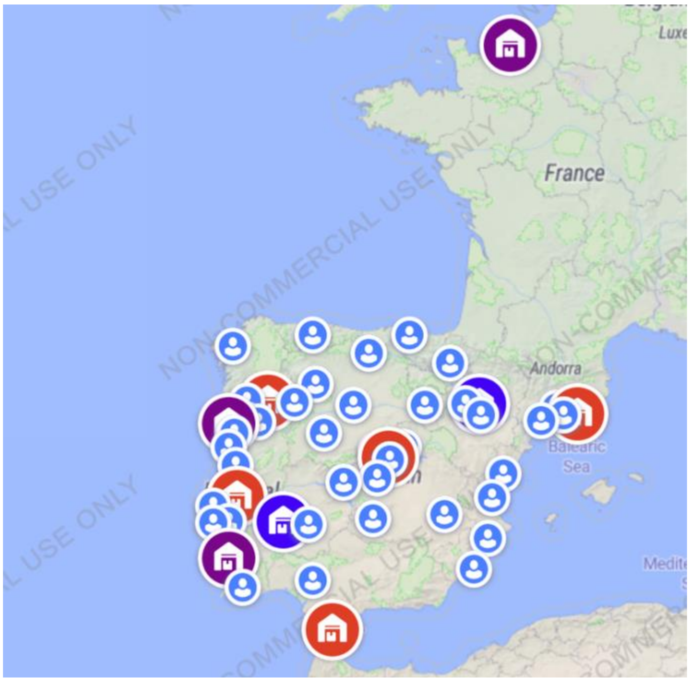

Figure 3.5: Simulation Model of Case Study – Detailed View of the Iberian Peninsula Region

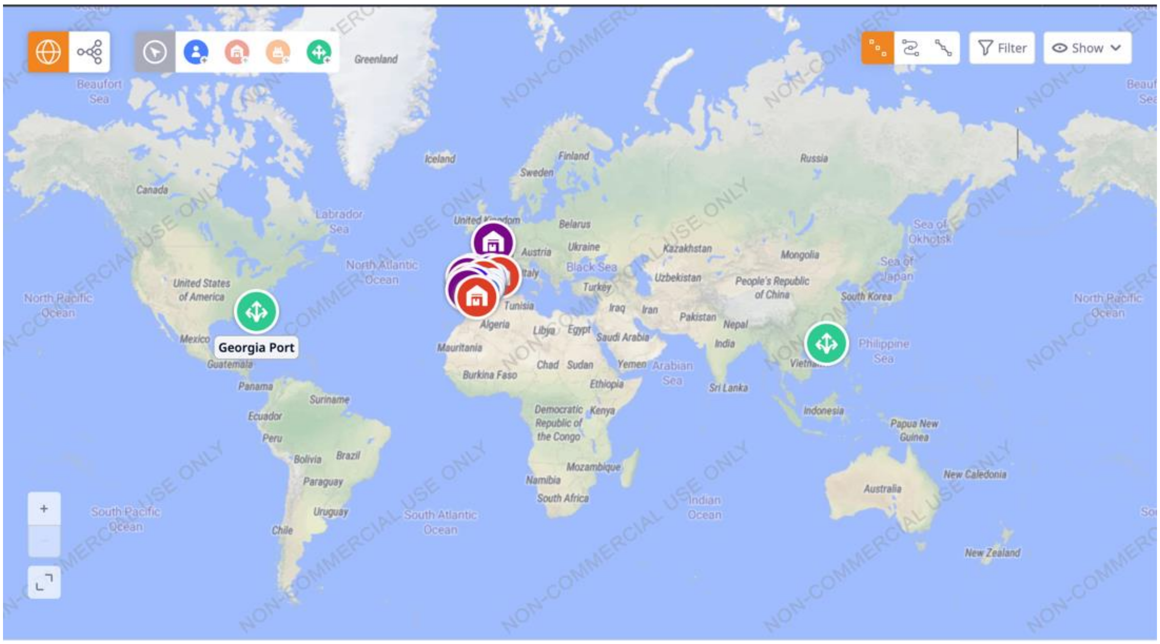

Figure 3.6: Simulation Model of the Case Study

3.4.1. Description of Case Study

The SC considered can be found in Figure 3.6, where the facilities and their locations are depicted.

The following facilities were considered:

I. 2 Suppliers located in America and Asia:

   a. Georgia; Hong Kong.

II. 3 Ports located in Portugal and France:

a. Sines; Leixões; Haropa.

III. 2 Logistic platforms located in Spain:

a. Zaragoza; Badajoz.

IV. 5 Distribution centers located across Spain and Portugal:

a. Entroncamento; Chaves; Gibraltar; Madrid; Barcelona.

V. 41 Customers located across the Iberian Peninsula grouped into 5 different regions based on their location:

a. Portugal North; Portugal South; Spain North; Spain Center; Spain South.

3.4.2. Assumptions

3.4.2.1. Customers Demand

The demand data for the case study includes various customer segments across the Iberian Peninsula, each with specific demand patterns for different products. Table A.1 in Appendix A, summarises the demand data, highlighting the periodic demand intervals, order quantities, and expected delivery times for each customer segment and product.

Each entry specifies the first occurrence, order interval, and quantity, essential for simulating the supply chain's response to demand. The demand type is periodic, indicating regular intervals for order placements. The normal distribution parameters provide variability in order intervals and quantities, reflecting real-world demand fluctuations.

3.4.2.2. Inventory Policies

The inventory policies for the case study define the stocking strategies at various facilities within the supply chain network. These policies ensure that each facility maintains adequate stock levels to effectively meet demand and manage supply chain disruptions. Table A.2 in Appendix A sum up the key inventory policies, including the facility locations, policy types, and stock levels.

The inventory policies for the case study have been carefully chosen to ensure the efficient management of stock levels across the supply chain. At ports, the policy of **Regular Safety Stock** is implemented to maintain a significant buffer of goods, ensuring a continuous supply despite the inherent variability in inbound shipments. Ports are critical entry points for goods into the supply chain, handling large volumes that necessitate higher safety stock levels and a substantial maximum level. On the other hand, the port check period is set at 30 days, reflecting the longer lead times associated with sea freight and the slower inventory turnover. This period allows sufficient time to detect and rectify inventory discrepancies without frequent interventions. Similarly, logistic platforms, which function as intermediate storage locations supporting both inbound and outbound logistics, utilize the same inventory policy. Like ports, platforms handle a significant volume of goods but with less frequent turnover than DCs. Therefore, a 30-day check period is appropriate, allowing for strategic adjustments rather than daily interventions.

For Distribution Centers (DCs), the inventory policy **Min-Max** strategy is employed. DCs are crucial in distributing products to customers and must respond highly to demand fluctuations. This policy provides the flexibility required to maintain optimal stock levels, ensuring that there is enough inventory to meet peak demands while avoiding overstocking and minimising holding costs. Given the high frequency of orders and rapid turnover rates at DCs, a daily check period is essential. Regular monitoring ensures inventory levels are promptly adjusted to meet daily demand variations, thereby maintaining high service levels.

3.4.2.3. Loading and Unloading Gates

Loading and unloading gates are considered only at the logistic platforms and in the DC Entroncamento, which are train destinations.

Each platform has a 2-hour processing time due to the transhipment process. This time was considered to ensure efficient cargo handling during the transfer between different transportation modes. These facilities are equipped with sufficient gates to handle the expected volume of goods, ensuring efficient processing and minimal delays.

3.4.2.4. Transportation Modes

For this dissertation, three modes of transportation are considered: boat, train and truck. These transportation modes were selected based on their relevance and practicality for the supply chain network under study. Each mode has distinct capacities and speeds, which are critical for simulating the movement of goods within the supply chain, as summarised in Table A.3 in Appendix A.

- Boat: Boats have the highest capacity of 3,320 cubic meters, allowing for the bulk transportation of goods over long distances. However, they have the slowest speed of 37 km/h. This mode is ideal for moving large volumes of goods across seas and oceans.
- Train: Trains have a capacity of 1,660 cubic meters and can travel at a speed of 75 km/h. They offer an efficient means of moving large quantities of goods over land, especially for long distances between major logistic hubs and distribution centers.
- Truck: Trucks have a capacity of 90 cubic meters and can travel at a speed of 80 km/h. This mode of transport is highly flexible and suitable for short to medium distances, providing a crucial link between ports, distribution centers, and end customers.

3.4.2.5. Transportation Time

Transportation times are crucial to this supply chain model, impacting delivery schedules, inventory levels, and overall efficiency. Given the variability and reliability differences across transportation methods, it is essential to model these times accurately.

A normal distribution is used to model transportation times for its simplicity and effectiveness in representing real-world variability around a central mean. The choice of the normal distribution is particularly suitable when delays and speeds are symmetrically distributed around the meantime, which is often the case for well-established transportation routes.

- Boats:
    - Reliability: Generally stable and less prone to delays.
    - Uncertainty Factors: Mainly affected by weather and port congestion, which are relatively predictable.
    - Standard Deviation: Set at 5% of the mean time to reflect high reliability.
- Trains:

    - Reliability: Rail transport is more reliable than road transport but can still experience delays due to scheduling conflicts, track maintenance, and operational issues.
    - Uncertainty Factors: Scheduling conflicts and track maintenance.
    - Standard Deviation: A moderate standard deviation of 10% of the mean transportation time is used to reflect this level of reliability.
- Trucks:
    - Reliability: Highly variable due to traffic, weather, and road conditions.
    - Uncertainty Factors: Numerous potential delays.
    - Standard Deviation: Set at 20% of the mean time to account for high variability.

Table A.4 in Appendix A presents the distances, vehicle types, mean transportation times, and standard deviations. This analytical approach considers the distinctive attributes and uncertainties of each mode of transportation, thereby enriching the authenticity of the supply chain model.

3.2.4.6. Shipping Policies

The case study follows standard shipping policies to guarantee consistency and reliability in the supply chain. These policies are critical for managing the supply chain and satisfying consumer demand on schedule. The main components are described in Table A.5 in Appendix A:

Full Truck Load (FTL) policy was adopted for all forms of transportation, including boats, trains, and trucks. The FTL policy requires that shipments be made only when the vehicle is completely loaded or reaches the minimum load ratio. This technique is cost-effective because it makes the best use of transportation capacity, lowering the cost per unit moved and reducing the number of trips required.

- Boat: A minimum load ratio of 0.7 was set for boats. The substantial capacity of boats justifies this greater ratio. At least 70% of a boat's capacity must be reached before departure to maximise the cost and efficiency of long-distance marine transport, which has significant fixed operating costs.
- Train: Trains have a minimum load ratio of 0.6. Trains balance capacity and speed, making them suitable for large volumes over land. A 60% load ratio ensures efficient use of rail capacity while allowing for some flexibility in scheduling.
- Truck: Trucks, more versatile and suited for shorter distances, have a minimum load ratio of 0.5. This lower ratio allows trucks to operate more frequently, providing flexibility and responsiveness to meet varying demand patterns.

All shipments were prioritised using **First in First Out (FIFO)**, to ensure that the products were dispatched in the order they arrived. This strategy is straightforward and fair, preventing older stock from becoming obsolete or expired, which is especially crucial for time-sensitive items.

Furthermore, unlike trucks and boats operating around the clock, trains follow a set timetable due to track availability and maintenance requirements. This means trains must conform to set departure schedules and cannot travel as freely as trucks and boats. The conditioned timetable of trains demands meticulous planning to coordinate with other modes of transportation and maintain smooth supply chain operations.

3.2.4.7. Sourcing Policies

The sourcing policies in the case study are intended to balance cost efficiency and lead time considerations, guaranteeing a reliable supply of goods whilst managing expenses. The key components of the sourcing policies are as follows in Table A.6 in Appendix A:

The **Uniform Split** policy at ports guarantees that incoming orders are dispersed uniformly among numerous sources. This technique helps to keep any single port from becoming overburdened with demand, which improves the overall efficiency and dependability of port operations. By spreading the load equitably, the risk of delays and bottlenecks is reduced, resulting in a smoother flow of items into the supply chain. Similarly, logistics platforms implement the same policy to ensure orders are evenly allocated among available providers. This equitable distribution helps maintain operational balance and efficiency.

The **Fastest** policy for distribution centers (DCs) emphasises sourcing from the quickest available provider. This guideline is critical for DCs because they are accountable for completing consumer requests quickly. By getting from the fastest suppliers, DCs may reduce lead times and ensure that goods are delivered to clients on time. This strategy is especially critical for maintaining excellent service standards and achieving customer expectations for on-time deliveries.

3.2.4.8. Cost per Km and CO2 Consumption

The costs and CO2 emissions are calculated using a **product & distance-based** method. This approach considers the volume of the product being transported and the distance it travels, ensuring a fair and proportional allocation of costs and emissions.

As Table A.7 in Appendix A presents, the costs are estimated depending on product volume and distance travelled, giving a comprehensive picture of the expenses relating to each mode of transportation. Similarly, CO2 emissions are estimated per unit distance, which provides insight into the environmental impact.

3.5. Conclusion

This chapter developed a comprehensive simulation-based framework to evaluate the effectiveness and sustainability of intermodal transportation routes across the supply chain. The detailed simulation model encompasses various components of a generic supply chain, including suppliers, ports, logistic platforms, distribution centers, and customers, providing a realistic representation of the supply chain dynamics. The model aims to optimise transportation routes, enhance resilience, and ensure efficient inventory and capacity management by incorporating strategic measures and assumptions.

The case study focuses on the Iberian Peninsula and its global connections, utilising the AnyLogistix software to simulate different scenarios and transportation strategies. Through this approach, the dissertation aims to identify vulnerabilities, optimise routes, and improve the overall performance of the supply chain.

4. Analysis of Alternatives

This chapter analyses three alternative multimodal transportation strategies within the supply chain network, which includes 2 products, 2 suppliers, 3 ports, 5 distribution centers, and 2 logistic platforms. Each alternative utilises rail, sea, and truck transport.

Alternative A represents normal conditions with balanced use of all transport modes. Moreover, Alternative B maximises rail transport for cost and environmental efficiency. Finally, Alternative C uses all three vehicle types but excludes one of the ports for increased flexibility and resilience.

The simulation results were obtained on a MacBook Pro 2019, averaging values from 20 replications, with each run taking approximately 5 minutes.

4.1. Alternative A

4.1.1. Description of Alternative A

Alternative A primarily focuses on trucks for most of the distribution network, ensuring flexibility and responsiveness in meeting customer demands. The graph representation in Figure 4.1 illustrates the flow of goods from suppliers to ports, logistic platforms, distribution centers, and finally to customers, highlighting the predominant use of road transport. This approach aims to balance efficiency and accessibility while leveraging the strengths of each transportation mode where most appropriate.

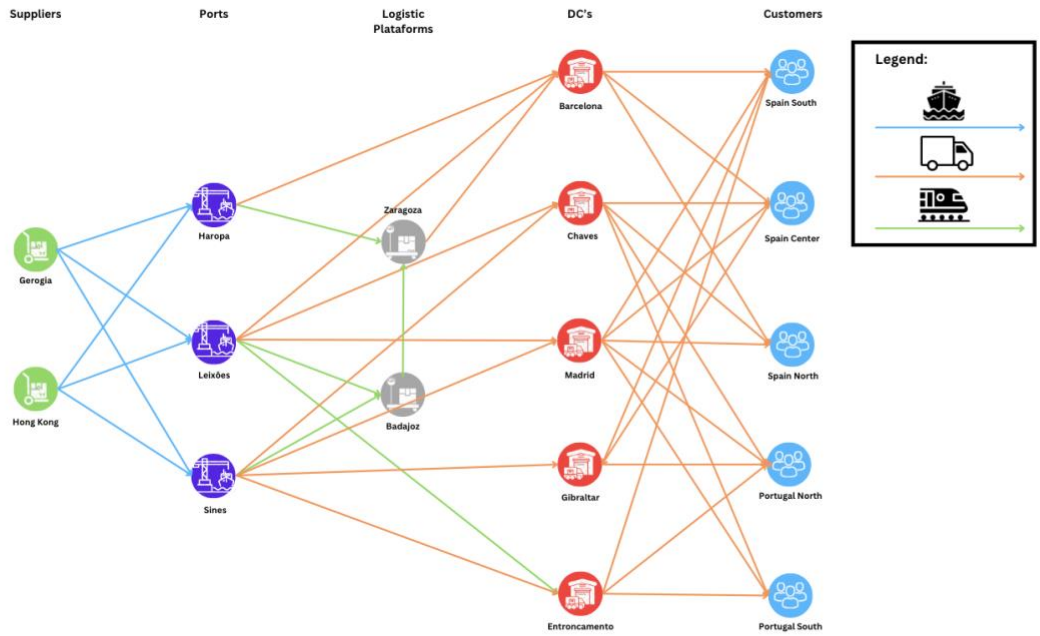

Figure 4.1: Graph Representation of Alternative A

4.1.2. Results of Alternative A

I. Service Level

As mentioned in Section 0, the service level is a critical performance metric in the supply chain, reflecting the ability to meet customer demand without stockouts.

The service level values in Table 4.1 represent the average percentage obtained over a simulation horizon of 2 years.

Table 4.1: Service Level by Customer Region and Product - Alternative A

Customer Region	**Product**	**Service Level (%)**
Portugal North	A	99,7
	B	99,7
Portugal South	A	99,8
	B	99,7
Spain North	A	99,6
	B	99,6
Spain Center	A	99,5
	B	99,5
Spain South	A	99,6
	B	99,5

The service levels were above 99%, demonstrating a reliable and strong supply chain. This suggests an idealised simulation model where demand is always met efficiently, possibly due to sufficient production and transportation capacities and robust inventory policies.

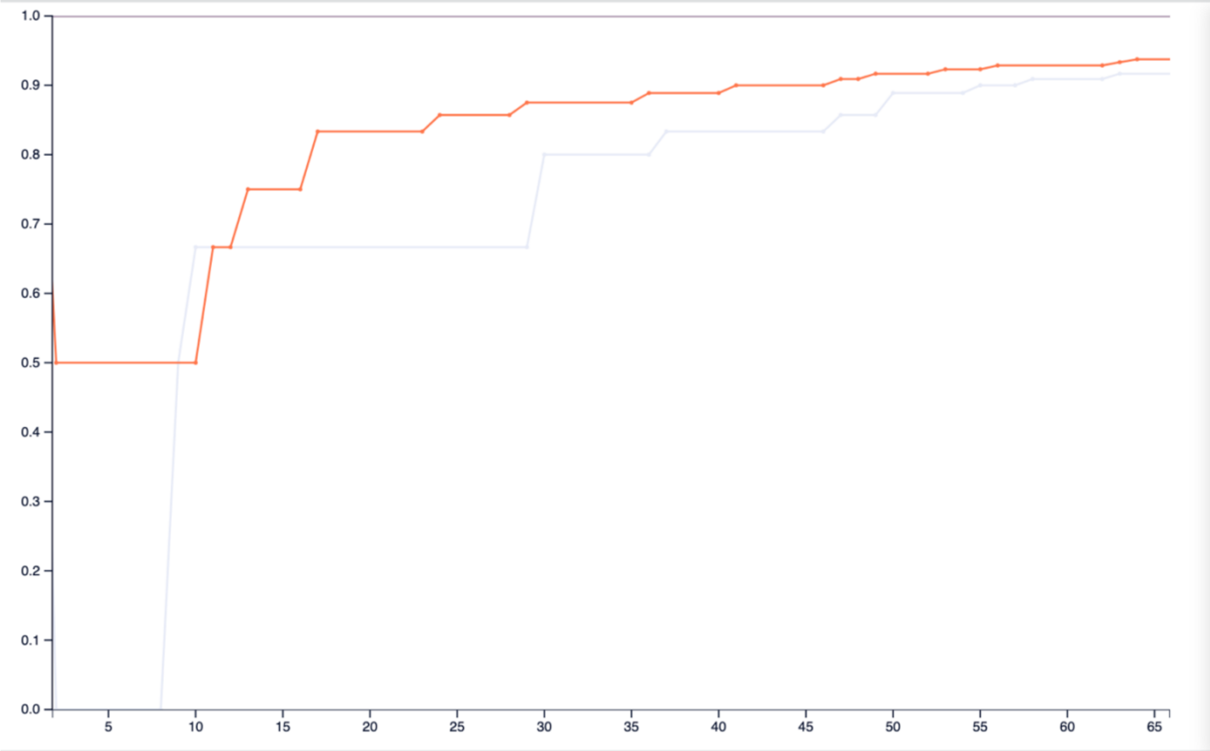

Figure 4.2: Service level variation at Barcelona DC in the first two months of simulation for Alternative A

In Figure 4.2, the variation in service level at the Barcelona distribution center during the first two months of the simulation is illustrated. The service level starts relatively low, since this

DC starts with only the initial stock, but increases steadily as demand is progressively met. This indicates an improvement in the distribution center's ability to fulfil orders and maintain higher service levels.

II. Inventory and Demand

The available daily inventory at various facilities represents the stock levels maintained to meet customer demand. The daily inventory levels for the DC Barcelona are depicted in Figure 4.3 below.

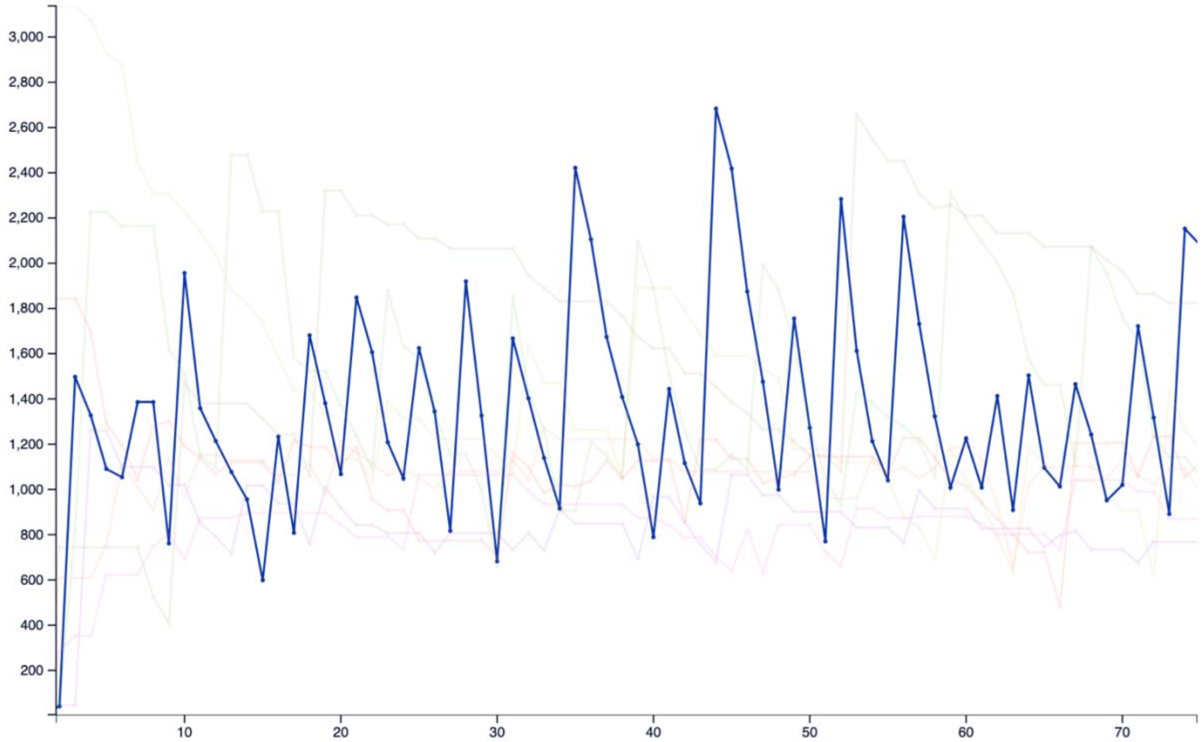

Figure 4.3: Daily Inventory for DC Barcelona in the first two months of simulation for Alternative A

The image above shows that although it presents considerable fluctuations, due to demand being met and restocking, the inventory is always with positive values.

All facilities met demand without backlogs, and these locations have no potential bottlenecks. Similarly, both Product A and Product B had no backlog, suggesting that their demand was fully met within the analysed period.

III. Costs

The transportation costs are analyzed by vehicle type to provide insights into which transportation modes are the most cost effective. For this analysis, a container refers to a standard Twenty-foot Equivalent Unit (TEU). Table 4.2 displays the total transportation costs and the cost per TEU for each vehicle type, in RMU (Relative Measurement Unit), at the end of the simulation.

Table 4.2: Total Transportation Cost - Alternative A

Vehicle Type	Total Transportation Cost (rmu)	Cost per TEU (rmu)
Boat	26,78 M	2,00 K
Train	320 K	1,00 K
Truck	35,05 M	5,00 K

The table above shows that trucks incur the highest transportation costs, followed by boats, with trains having the lowest.

Table 4.3 provides a breakdown of overall inventory and transportation costs, offering a comprehensive insight into the financial expenditures within the supply chain.

Table 4.3: Cost Categories – Alternative A

Cost Category	Value (rmu)
Transportation Cost	62,21 M
Inventory Cost	66,65 M

Inventories spending is the largest cost factor, highlighting efficient inventory management's importance in reducing overall expenses.

IV. Sustainability indicators

The CO2 emissions (in metric tons) for the 2 years of simulation horizon, from all vehicle types, are summarised in Table 4.4. This breakdown helps identify the most environmentally impactful modes of transportation.

Table 4.4: CO2 Emissions by Vehicle Type – Alternative A

Vehicle Type	CO2 Emissions (tCO2)
Boat	21,43 M
Train	598,44 K
Truck	38,24 M

Trucks are the largest contributors to CO2 emissions. At the same time, trains are the most sustainable alternative, suggesting that optimising truck usage and expanding rail transport could significantly reduce the supply chain's carbon footprint.

4.2. Alternative B

4.2.1. Description of Alternative B

Alternative B focuses on utilising different transportation modes to enhance overall supply chain performance, which is crucial for optimizing sustainability and efficiency in the dissertation. Unlike Alternative A, which relies heavily on trucks, Alternative B increases the use of rail transportation for long-distance routes.

This adjustment leverages rail transport's efficiency and lower environmental impact. Truck usage remains predominant for last-mile deliveries, ensuring that goods reach their final destinations efficiently. All other operating conditions remain the same as in Alternative A.

The graph in Figure 4.4 emphasizes the increased use of rail transport.

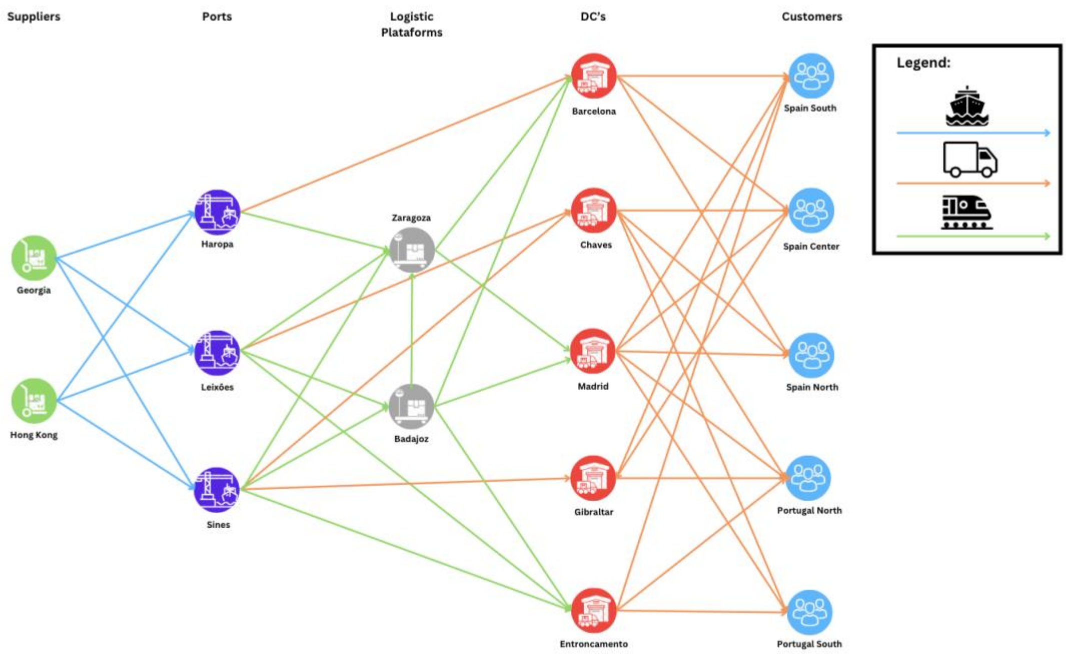

Figure 4.4: Graph Representation of Alternative B

4.2.2. Results of Alternative B

I. Service Level

The service level values in Table 4.5 represents the average value of 20 simulations and percentages obtained over a simulation horizon of 2 years for Alternative B.

Table 4.5: Service Level by Customer Region and Product - Alternative B

Customer Region	Product	Service Level (%)
Portugal North	A	94,0
	B	93,8
Portugal South	A	94,8
	B	94,9
Spain North	A	94,5
	B	94,7
Spain Center	A	94,5
	B	94,5
Spain South	A	94,4
	B	94,3

The service level analysis shows that the supply chain of Alternative B is very effective at meeting customer demand across various geographies and product categories. Table 4.5 shows that the service levels for different client groups are all higher than 93.0%, which suggests a dependable and strong supply network capable of meeting orders effectively but with room for enhancement.

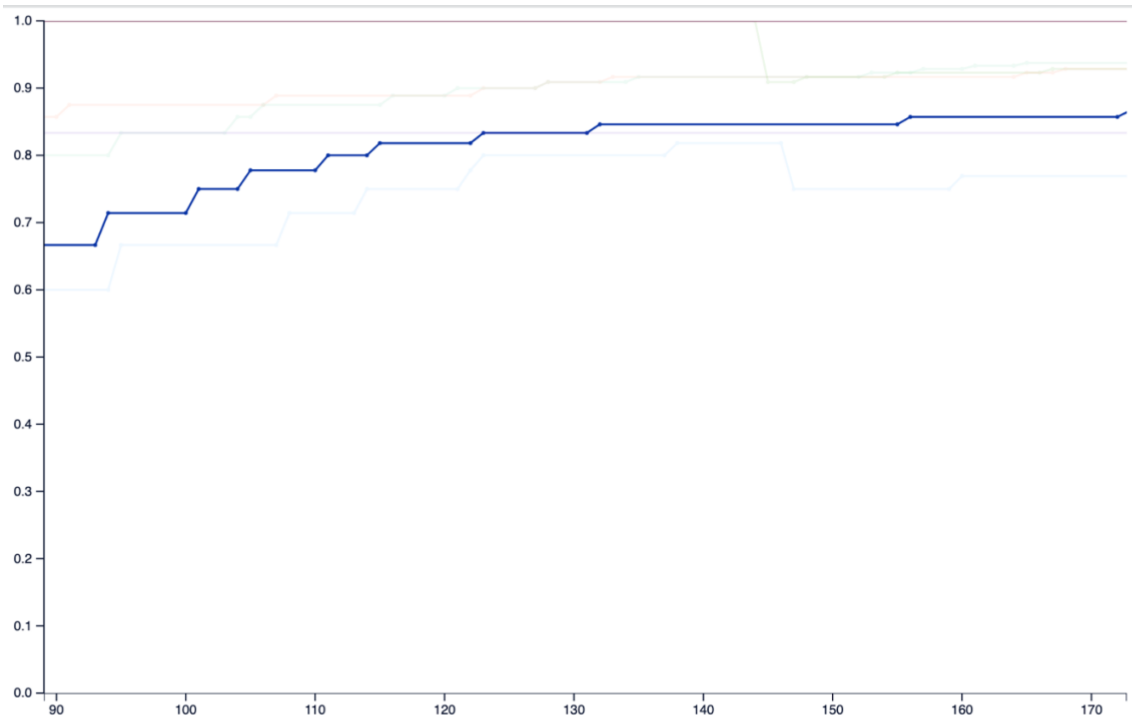

Figure 4.5: Service level variation at Barcelona DC during two months of simulation for Alternative B

In Figure 4.5, the variation in service level at the Barcelona distribution center during the period from day 90 to day 170 of the simulation is illustrated. The service level starts at around 65% and increases steadily, eventually reaching approximately 85%. This steady increase indicates an improvement in the distribution center's ability to fulfill orders and maintain higher service levels over time.

II. Inventory and Demand

The values presented in Table 4.6 represent the final demand backlog for each product at each distribution center, averaged over 20 simulation runs. These values are approximated to units and cubic meters (m^3), providing a clear understanding of the demand backlog distribution across the distribution centers in Alternative B.

It is observed that the distribution centers in Madrid and Barcelona have minimal backlogs for Product B, while Entroncamento exhibits significant backlogs for both products. The presence of backlogs in these specific DCs indicates potential bottlenecks in fulfilling demand efficiently.

It is also important to note that other distribution centers not listed in Table 4.6 have zero backlogs for each product, reflecting their ability to meet demand without any delays or shortages. This highlights the efficiency of these DCs in managing their inventory and fulfilling orders promptly.

Table 4.6: Demand Backlog by DC and Product – Alternative B

Distribution Center	Product	Demand Backlog (m³)
Madrid	A	0
	B	50
Barcelona	A	0
	B	55
Entroncamento	A	1513
	B	615

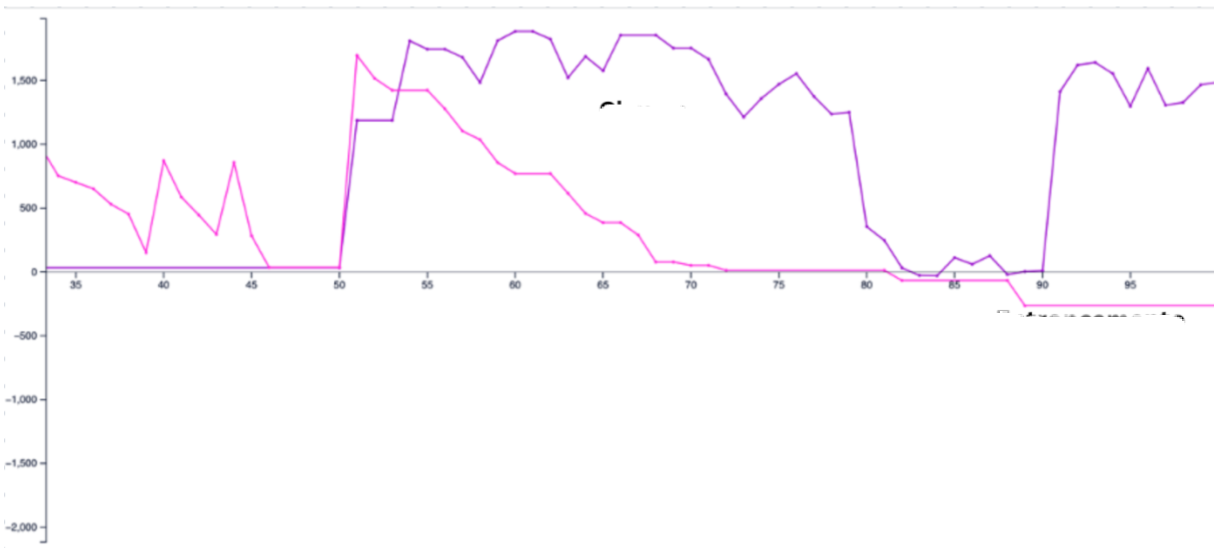

Figure 4.6: Daily Inventory in DCs Chaves and Entroncamento - Alternative B

The graphic above in Figure 4.6 depicts the daily inventory levels over two months for the distribution centers (DCs) in Chaves (purple line) and Entroncamento (pink line). The distinct lines represent the inventory trends for each DC.

For Chaves, the inventory levels show minor fluctuations but generally remain within a narrow range. There are occasional peaks, suggesting periods of higher stock intake or lower demand, allowing the inventory to build up temporarily. The stable trend indicates a well-balanced supply chain, where supply and demand are closely matched. In Entroncamento, significant drops below zero occur multiple times, pointing to recurring issues with meeting demand. The graph shows periods of recovery where inventory levels rise, but these are followed by sharp declines, suggesting that Entroncamento faces challenges in maintaining a consistent inventory flow. The repeated dips below zero indicate a cycle of shortages and recovery, which disrupts operations and customer satisfaction.

III. Costs

Table 4.7 displays the total transportation costs and the cost per TEU for each vehicle type, in rmu, at the end of the simulation.

Table 4.7: Total Transportation Cost - Alternative B

Vehicle Type	Total Transportation Cost (rmu)	Cost per TEU (rmu)
Boat	25,89 M	1,93 K
Train	898,73 K	0,75 K
Truck	23,53 M	4,31 K

The table above shows that in this alternative, boats are the highest transportation cost, followed closely by trucks and lastly, trains.

Table 4.8 provides a breakdown of overall inventory and transportation costs, offering a comprehensive insight into the financial expenditures within the supply chain.

Table 4.8: Cost Categories – Alternative B

Cost Category	Value (rmu)
Transportation Cost	50,32 M
Inventory Cost	63,89 M

Inventories spending is the largest cost factor, highlighting efficient inventory management's importance in reducing overall expenses.

IV. Sustainability indicators

The CO2 emissions for each vehicle type are in Table 4.9.

Table 4.9: CO2 Emissions by Vehicle Type – Alternative B

Vehicle Type	CO2 Emissions (tCO2)
Boat	20,71 M
Train	1,44 M
Truck	25,67 M

As the table below shows, trucks are the largest contributors to CO2 emissions. Boats also contribute significantly, primarily due to the necessity of long-distance maritime transportation. Conversely, trains have the lowest CO2 emissions, making them the most sustainable alternative.

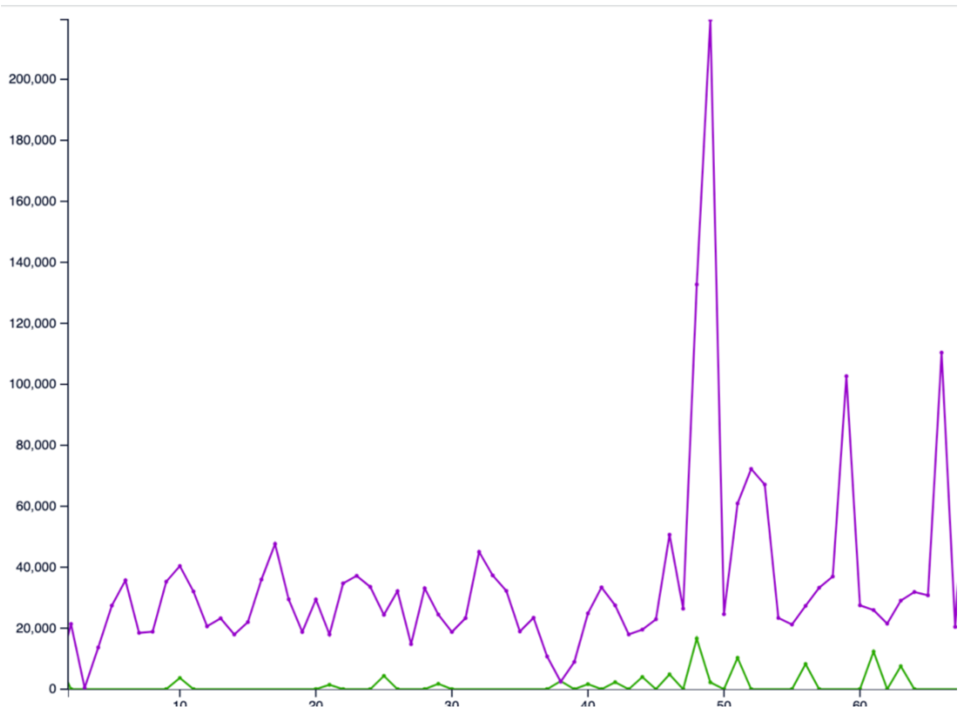

Figure 4.7: CO2 Emissions of Trains and Trucks - Alternative B

As can be observed in Figure 4.7, the CO_2 emissions of trucks (in purple) are significantly higher than those of trains (in green). This substantial difference underscores the necessity of incorporating greater train usage within the supply chain to reduce the overall carbon footprint.

4.3. Alternative C

4.3.1. Description of Alternative C

Alternative C modifies the configuration used in Alternative A by focusing on suppressing the Haropa Port due to its low utilisation, emphasising the importance of optimising port usage for improved efficiency.

All other components and assumptions remain consistent with Alternative A, ensuring comparability of results across alternatives. The graph in Figure 4.8 illustrates the updated network configuration with the removal of Haropa Port.

As it is possible to observe by the graph, the use of rail transport is minor, whereas use of truck is predominant. Moreover, there will be higher stress in the ports of Leixões and Sines, with the removal of Haropa from the SC. The two ports will need maintain supply to the five distribution centers and the same five customer groups.

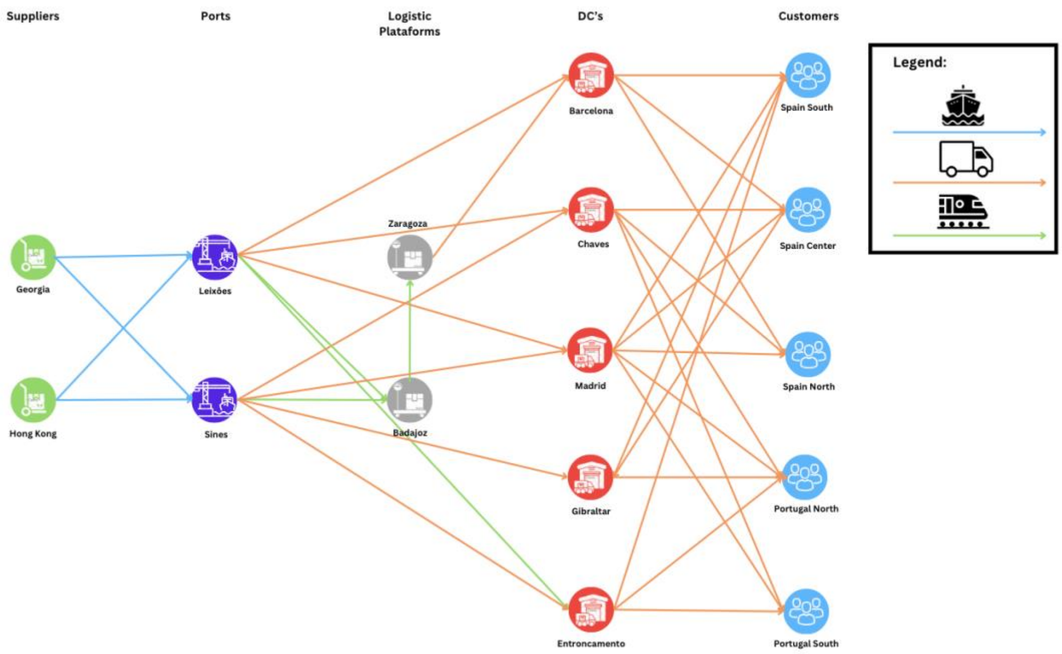

Figure 4.8: Graph Representation of Alternative C

4.3.2. Results of Alternative C

I. Service Level

The service level values in Table 4.10 represent the average value of 20 simulations and percentages obtained over a simulation horizon of 2 years for Alternative C.

The analysis of service levels indicates that the supply chain in Alternative C performs well in fulfilling customer demand across diverse regions and product types. As depicted in Table 4.10, this alternative demonstrates a reliable and robust supply network that effectively meets orders. However, there is still potential for further improvement.

Table 4.10: Service Level by Customer Region and Product - Alternative C

Customer Region	Product	Service Level (%)
Portugal North	A	90,6
	B	90,7
Portugal South	A	91,2
	B	91,2
Spain North	A	89,7
	B	89,9
Spain Center	A	90,2
	B	89,6
Spain South	A	91,4
	B	91,3

II. Inventory and Demand

The values in Table 4.11 represent the final demand backlog for each product at the DC Barcelona, averaged over 20 simulation runs. These values are approximated to units and cubic meters (m^3).

Table 4.11: Demand Backlog by DC and Product – Alternative C

Distribution Center	Product	Demand Backlog (m^3)
Barcelona	A	22506
	B	9011

The table above indicated that Barcelona has significant backlogs for both products. These substantial backlogs demonstrate the difficulty this DC faces in meeting all demands efficiently.

It is also important to note that other distribution centers not listed in Table 4.11 have zero backlogs for each product, reflecting their ability to meet demand without delays or shortages. This highlights the efficiency of these DCs in managing their inventory and fulfilling orders promptly.

III. Costs

Table 4.12 displays the total transportation costs and the cost per TEU for each vehicle type, in rmu, at the end of the simulation.

Table 4.12: Total Transportation Cost - Alternative C

Vehicle Type	Total Transportation Cost (rmu)	Cost per TEU (rmu)
Boat	24,66 M	1,84 K
Train	66,90 K	1,00 K
Truck	25,29 M	3,61 K

The table above shows that in this alternative, trucks are the highest transportation cost, followed closely by boat and lastly, trains, with a significantly lower value.

Table 4.13 provides a breakdown of overall inventory and transportation costs, offering a comprehensive insight into the financial expenditures within the supply chain.

Table 4.13: Cost Categories – Alternative C

Cost Category	Value (rmu)
Transportation Cost	50,02 M
Inventory Cost	61,40 M

Inventories spending is the largest cost factor, highlighting efficient inventory management's importance in reducing overall expenses.

IV. Sustainability indicators

The CO2 emissions for each vehicle type are in Table 4.14.

Table 4.14: CO2 Emissions by Vehicle Type – Alternative C

Vehicle Type	CO2 Emissions (tCO2)
Boat	19,72 M
Train	107,04 K
Truck	27,59 M

As the table below shows, trucks are the largest contributors to CO2 emissions. Boats also contribute significantly, primarily due to the necessity of long-distance maritime transportation. Conversely, trains have the lowest CO2 emissions due to low use.

4.4. Comparative Analysis

I. Alternative A:

Alternative A demonstrates several advantages and disadvantages in its approach. One of the key advantages is its high service levels, maintaining a service level above 99% for all customer regions and products. This indicates a high reliability in meeting customer demand. Additionally, the heavy reliance on trucks provides significant flexibility and responsiveness, allowing for quick adjustments to demand fluctuations and route changes.

However, Alternative A also has notable disadvantages. It incurs the highest total transportation cost, with the highest cost per TEU for trucks, making it the most expensive option. Furthermore, it results in the highest CO2 emissions (3,824 tCO2) due to extensive truck usage, making it the least sustainable option. It also relies heavily on road infrastructure, which can be susceptible to traffic congestion and road maintenance issues.

II. Alternative B:

Alternative B offers a contrasting approach with several distinct advantages. It exhibits the lowest transportation cost (898.73 K rmu) due to the efficient use of rail transport, which has the lowest cost per TEU. Additionally, it shows the lowest CO2 emissions (59.84K tCO2) thanks to the predominant use of rail transport, which is significantly more environmentally friendly. Like Alternative A, it maintains a service level above 99%, indicating high reliability.

However, Alternative B also has disadvantages. Its dependency on rail can pose challenges under certain disruptions, such as rail strikes, which could impact the supply chain's ability to maintain service levels. It also requires robust rail infrastructure, which may not be available in all regions, potentially limiting its applicability in some areas. Furthermore, rail transport may offer less flexibility than road transport, especially for last-mile deliveries.

III. Alternative C:

Alternative C provides a balanced approach, leveraging the strengths of all transportation modes and offering moderate performance across all metrics. It presents moderate transportation costs and CO2 emissions, falling between Alternatives A and B, thus compromising cost efficiency and sustainability.

Despite these advantages, Alternative C also has its drawbacks. It presents the lowest service levels of the three alternatives, indicating some difficulties in meeting customer demand. This could be a significant concern for maintaining high customer satisfaction and reliability.

4.5. Validation of the Simulation Model

There is no fully conclusive approach for validating the proposed system's model, particularly when dealing with such complex systems. According to (Law, 2022), the most convincing indicator of a simulation model's validity is that its output data closely resembles the current system behaviour. However, collecting information from a real Supply Chain network and analysing its performance statistics can be incredibly challenging due to its complexity and variety. As a result, simulation data cannot be directly compared to real data.

Regardless, the simulation findings should be evaluated. Suppose the results correspond to how the system's activities are seen, and the model is accurate for the given objectives. In that case, the simulation model is said to have face validity (Robinson, 2000). Depending on the model's intended use and the decision-maker's utility function, various levels of accuracy will be required (Robinson, 2000).

Considering: (i) all the requirements and assumptions collected after extensive bibliographical research on multimodal transportation networks presented in Section **Error! Reference source not found.**; (ii) the simplifications, also detailed in Section **Error! Reference source not found.**, for an adequate level of abstraction such that the model is useful; (iii) to understand the impact of different transportation network strategies on the global SC performance; (iv) SC behaviour shows evidence of being realistic enough through concepts normally observed in SC; it is possible to validate the simulation model.

After carefully considering these variables, it is possible to determine that the simulation model is appropriate for the goals stated in this dissertation. Because the model's output closely approximates the behaviour of real-world supply chains, it fulfils the requirements for face validity and offers a reliable tool for examining multimodal transportation network designs. Thus, the model is considered valid for the purposes outlined in this dissertation.

5. Robustness Analysis

As the main goal of this dissertation is to develop a simulation tool capable of testing the resilience of a multimodal transport supply chain, two different scenarios will be presented as illustrative examples. These scenarios are designed to subject the three alternatives to stress conditions and assess its performance. This approach aims to identify critical points within the supply chain and proactively define targeted strategies to enhance overall resilience. Additionally, the goal is to determine which alternative performs better for the decision-making actor's goals.

5.1. Scenario 1: Demand Increase

Economic expansions are common scenarios that can greatly impact supply chain operations. These periods of economic growth are characterised by increased consumer spending and higher demand for goods. For a multimodal transport supply chain, the implications of an economic expansion are extensive, affecting demand, transportation costs, lead times, inventory levels, operational efficiency, and supplier stability. Understanding these impacts is crucial for developing strategies to capitalise on growth opportunities and ensure supply chain efficiency.

For this dissertation, the impacts to be considered from this economic expansion are as follows: (i) increased consumer demand; (ii) decrease in order intervals; (iii) increase in transportation costs.

5.1.1. New Assumptions

These new assumptions will be applied uniformly across all three alternatives (A, B, and C). The characteristics and parameters for each alternative will remain unchanged except for the adjustments mentioned below.

5.1.1.1. Demand and Order Frequency

Demand quantities will be increased by 20% to reflect the surge in consumer spending during an economic expansion. This adjustment simulates the increased volume of goods moving through the supply chain and the corresponding impact on production schedules and inventory management.

Additionally, order intervals will be decreased by 10% to simulate more frequent purchasing patterns. This change reflects the higher consumption rate and frequent replenishment requirements during periods of economic growth.

Both new values are represented in Table B.1 in Appendix B.

5.1.1.2. Transportation Costs

Transportation costs per kilometer will increase by 15% due to higher fuel prices driven by increased demand and market activity. This adjustment models the increased cost burden on the supply chain. Therefore, there is a need to re-evaluate transportation modes and routes to optimise costs. These values are showcased in Table B.2 in Appendix B.

5.1.1.3. Operational Adjustments

Unloading times will be increased by 100% to account for handling the higher cargo volume. This adjustment mirrors the impact of increased cargo volumes on operational processes, requiring more time to unload the additional goods at warehouses and distribution centers. Specifically, the transhipment will now be considered as 4 hours.

5.1.2. Scenario Simulation Results

5.1.2.1. Service Level

Table 5.1 below compares the average SL of 20 simulation runs for the three alternatives across various customer groups and products. It highlights the effectiveness of each alternative in meeting customer demand in different regions.

Table 5.1: Service Level by Customer Group and by Product – First Scenario

Customer Group	Product	SL Alternative A (%)	SL Alternative B (%)	SL Alternative C (%)
Portugal North	A	76,4	64,3	62,9
	B	74,2	73,4	63,6
Portugal South	A	77,1	59,6	64,0
	B	76,9	71,2	62,1
Spain North	A	76,3	61,3	63,8
	B	75,4	69,8	63,7
Spain Center	A	75,6	59,4	63,3
	B	74,2	68,6	63,8
Spain South	A	76,5	60,6	64,2
	B	74,8	70,7	62,4

In summary, Alternative A emerges as the most robust option for maintaining high service levels across various regions and products. Alternative B shows potential but requires targeted improvements, while Alternative C needs significant enhancement to effectively meet the service level demands.

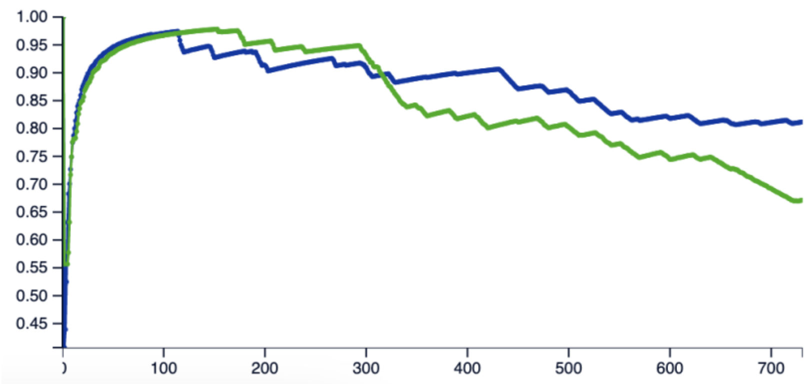

Figure 0.1: Service Level for Product - Alternative A / Scenario 1

Figure 5.1 illustrates the service level for Product A (blue line) and Product B (green line) under Alternative A in Scenario 1. Initially, both products exhibit high service levels, with Product A maintaining a slightly higher level than Product B. Over time, the service levels for both products decline, with Product B experiencing a more pronounced decrease. This trend indicates potential challenges in sustaining service levels for Product B compared to Product A over the simulation period.

5.1.2.2. Inventory and Demand

The average final backlog by DC and product across alternatives is shown in the table below.

Table 0.1: Backlog by Facility and by Product – First Scenario

Distribution Center	Product	Alternative A Backlog	Alternative B Backlog	Alternative C Backlog
Madrid	A	0	37375	0
	B	455	10302	6091
Barcelona	A	0	151140	0
	B	6573	39649	65162
Entroncamento	A	529	24977	1170
	B	1477	6912	4402
Gibraltar	A	676	0	0
	B	808	0	503
Chaves	A	0	0	0
	B	0	0	320

These results provide insight into the backlog variations across different facilities and products under various alternatives, reflecting the operational challenges. Table 0.1, averaged over 20 simulation runs, helps to identify which distribution centers and products experience higher backlogs and may require targeted strategies to improve efficiency and reduce delays.

5.1.2.3. Costs

The averaged total cost analysis by vehicle type and alternative is presented in Table 0.2 below.

Table 0.2: Costs by Vehicle Type and by Alternative – First Scenario

Vehicle Type	Total Cost Alternative A (rmu)	Total Cost Alternative B (rmu)	Total Cost Alternative C (rmu)
Boat	38,47 M	26,64 M	35,44 M
Train	302,31 K	375,20 K	79,60 K
Truck	44,50 M	23,72 M	41,78 M

These cost analyses highlight the financial implications of different transportation modes.

The different costs associated with transportation and inventory management are presented below in Table 0.3.

Table 0.3: Transportation and Inventory Costs - Comparison Between Alternatives

Cost Category	Alternative A (rmu)	Alternative B (rmu)	Alternative C (rmu)

Transportation	82,09 M	58,13 M	76,02 M
Inventory	83,87 M	50,53 M	75,53 M

The values presented in the table above are the average total costs for each category, by alternative.

5.1.2.4. Sustainability Indicators

The sustainability indicators, specifically CO2 production by vehicle type, are compared across alternatives as follows in Table 0.4. This comparison highlights the environmental impact of each alternative in terms of carbon emissions.

Table 0.4: CO2 Production by Vehicle Type – First Scenario

Vehicle Type	Alternative A (tCO2)	Alternative B (tCO2)	Alternative C (tCO2)
Boat	26,76 M	18,53 M	20,81 M
Train	1,26 M	1,45 M	432,78 K
Truck	42,21 M	22,50 M	36,38 M

The CO2 production analysis reveals that Alternative B achieves the lowest emissions overall, especially in boat and truck transportation, making it the most environmentally friendly option.

5.1.3. Conclusions on the Impact of the First Scenario on Supply Chain Performance

This first scenario simulation results reveal critical insights into the performance and efficiency of the supply chain under various alternatives. The analysis covered four key areas: service level, inventory and demand, costs, and sustainability indicators.

5.1.3.1. Alternative A

Alternative A presents the advantage of best service levels, consistently showing the highest service levels across all customer groups and products. Additionally, the backlog levels are moderate across facilities, indicating a balanced supply chain with manageable operational challenges, and it also presented the lowest levels of backlog overall.

However, it incurs the highest transportation and inventory costs, with transportation costs at 82.09 M (rmu) and inventory costs at 83.87 M (rmu). Moreover, this scenario also produces the highest CO2 emissions. While this alternative ensures high service levels, the associated costs and environmental impact are significant.

5.1.3.2. Alternative B

This alternative offers the advantage of lower costs, with the lowest costs across transportation and inventory, having transportation costs at 58.13 M (rmu) and inventory costs at 50.53 M (rmu). It also shows reduced CO2 emissions, particularly from trains and trucks. However, there is a noticeable drop in service levels across customer groups and products compared to Alternative A. Facilities like Barcelona experience a significant backlog, indicating potential bottlenecks and operational inefficiencies, and it has the highest numbers of backlog across all alternatives. This alternative achieves cost efficiency and reduces environmental impact, leading to decreased service levels and increased backlog in some facilities. It is crucial to focus on improving service levels while maintaining cost efficiency.

5.1.3.3. Alternative C

Alternative C balances costs and CO_2 emissions, presenting a middle ground with transportation and inventory costs. CO_2 emissions are also moderate across all vehicle types. Although it presents significant backlog values in some distribution centers, specifically Barcelona, the total backlog is still lower than Alternative B. However, this alternative shows the lowest service levels across all customer groups and products. For instance, the service level for Portugal South drops to 62.1% in Product B. Alternative C offers a balanced approach regarding costs and sustainability but struggles with maintaining service levels and managing product backlog. Strategic interventions to enhance service levels without escalating costs are necessary.

5.1.3.4. Overall Insights

The simulation results highlight key areas for improvement across the different alternatives:

I. Service Levels: High service levels require a trade-off between costs and environmental impact. Alternative A excels in service but at a high cost and emissions, while alternatives B and C need improvements in service quality.

II. Costs: Cost efficiency is best achieved in Alternative B, but operational inefficiencies must be addressed to avoid service-level compromises.

III. Sustainability: Alternative B is the most sustainable, demonstrating the feasibility of reducing CO_2 emissions while managing costs, though service levels need enhancement.

By balancing all these variables, the insights reveal that while cost and sustainability are important, service quality should not be overlooked. It depends on the goals of the decision-maker which alternative to choose, depending on whether the preference is to prioritize service levels, sustainability factors, or cost reduction. Successful supply chain management will require a comprehensive approach covering cost efficiency, sustainability, and excellent service levels.

5.2. Scenario 2: Introduction of New Product in the Spanish Market

Introducing a new product, Product C, into the supply chain represents a significant change with extensive implications in the SC. This new product has unique characteristics that will impact demand, lead times, inventory levels, and operational efficiency. Understanding these impacts is crucial for developing strategies to integrate Product C smoothly into the existing supply chain.

5.2.1. New Assumptions

Assumptions will remain consistent with those outlined in the case study, with only a few modifications.

5.2.1.1. Demand and Order Frequency

The introduction of Product C will alter demand patterns. The periodic demand intervals, order quantities, and expected delivery times for each customer segment specific to Product C are outlined in Table C.1 in Appendix C.

Each entry specifies Product C's first occurrence, order interval, and quantity. The demand type remains periodic, with normal distribution parameters providing variability in order intervals and quantities, reflecting real-world demand fluctuations.

5.2.1.2. Sourcing Policies

The sourcing policies for the new Product C scenario aim to balance cost efficiency and lead time considerations, ensuring a reliable supply of goods while managing expenses effectively. All policies will remain the same; the only difference is that both suppliers will also have Product C.

As in Alternative A, the Uniform Split policy will be applied from the suppliers to the ports.

5.2.1.3. Limited Geography

Product C will initially be introduced only in Spain to test its impact on the supply chain.

Therefore, the customer groups to be affected by this scenario are: (i) Spain North; (ii) Spain Center; (iii) Spain South.

5.2.1.4. Transportation Time

Transportation time will be decreased by 20% to meet the needs of the new product. This reduction is achieved through optimized routing, faster transportation modes, and improved coordination with logistics providers.

New values are presented in Table C.2 in Appendix C.

5.2.2. Second Scenario Simulation Results

5.2.2.1. Service Level

Table 0.5 below compares the average final SL of 20 simulation runs for the three alternatives across various customer groups and products.

Overall, Alternative A consistently achieves the highest service levels across most customer groups and products, indicating its effectiveness in maintaining service quality. However, it is important to consider this alternative's associated higher costs and environmental impacts. Alternative C provides a balanced approach, achieving high service levels in most scenarios and outperforming other alternatives in specific instances, such as for Product C in Spain North and Spain South. This suggests Alternative C can be a viable option for balancing service levels and sustainability. Alternative B shows lower service levels compared to A and C, particularly in Product C categories, indicating potential inefficiencies. However, it has the advantage of lower costs and reduced CO2 emissions, making it suitable for cost-conscious scenarios.

In conclusion, while Alternative A consistently provides the highest service levels, it comes at a significant cost and environmental impact. Alternative C emerges as a strong contender, offering a balanced approach to service levels and sustainability. Alternative B, although lagging in service performance, excels in cost efficiency and environmental considerations. Therefore, the choice between these alternatives should be guided by the strategic priorities of cost, service quality, and environmental sustainability.

Table 0.5: Service Level by Customer Group and by Product – Second Scenario

Customer Group	Product	SL Alternative A (%)	SL Alternative B (%)	SL Alternative C (%)
Portugal North	A	94,3	79,6	93,4
	B	98,1	79,2	97,6
Portugal South	A	95,6	79,4	94,5
	B	94,8	79,2	99,2
Spain North	A	93,2	79,4	93,8
	B	93,3	79,3	99,6
	C	44,1	32,2	51,5
Spain Center	A	96,1	79,1	94,1
	B	93,2	79,4	98,9
	C	39,8	31,9	51,3
Spain South	A	94,4	79,4	94,3
	B	95,2	79,5	99,7
	C	35,7	31,8	51,1

5.2.2.2. Inventory and Demand

The average final backlog by DC and product across alternatives is shown in Table 0.6.

Alternative A achieves the lowest backlog across most facilities and products, showcasing its effectiveness in supply chain management and maintaining minimal backlog levels. On the other hand, Alternative B experiences significant backlogs, particularly for Product A in Madrid and Barcelona and Products A and B in Entroncamento, highlighting potential inefficiencies in balancing supply and demand. However, it performs well for Product B and certain cases of Product C. While showing moderate backlogs, Alternative C performs better than Alternative B but not as efficiently as Alternative A. It manages some backlog for Product C in various distribution centers but generally keeps them within manageable limits.

This general analysis indicates that Alternative A is the most effective in keeping backlog levels low across most distribution centers and products, despite its higher costs and environmental impact. While Alternative B is cost-efficient, it faces significant backlog issues in several cases, suggesting inefficiencies that might impact service levels. Alternative C strikes a balance with moderate backlog levels and better performance in some specific situations than Alternative B. To select an option that best meets strategic goals, consideration should be given to the trade-offs between cost, service quality, and backlog management.

Table 0.6: Backlog by Facility and by Product – Second Scenario

Distribution Center	Product	Alternative A Backlog	Alternative B Backlog	Alternative C Backlog
Madrid	A	0	12708	1132
	B	0	0	0
	C	5108	5539	3011
Barcelona	A	0	40649	0
	B	1278	0	0
	C	15997	17055	10880
Entroncamento	A	135	8488	0
	B	1477	0	0
Gibraltar	A	0	0	203
	B	808	0	0
	C	3612	1383	2708
Chaves	A	0	0	0
	B	0	0	0

5.2.2.3. Costs

The averaged final cost analysis by vehicle type and alternative is presented in Table 0.7.

Table 0.7: Costs by Vehicle Type – Second Scenario

Vehicle Type	Alternative A	Alternative B	Alternative C
Boat	26,85 M	24,18 M	24,84 M
Train	341,55 K	738,50 K	628,72 K
Truck	36,14 M	24,31 M	31,45 M

Alternative A incurs the highest boat and truck transport costs, while Alternative B has the lowest costs for these modes. Conversely, Alternative C, although moderately cost-efficient for boats, shows the highest costs for train transport. Overall, Alternative B is the most cost-effective in boat and truck transport, while Alternative C offers a balanced approach with moderate costs across all transport modes.

The different costs associated with transportation and inventory management are presented below in Table 0.8

Table 0.8: Transportation and Inventory Costs – Second Scenario

Statistics	Alternative A	Alternative B	Alternative C
Transportation	63,61 M	53,73 M	56,48 M
Inventory	66,81 M	60,16 M	60,51 M

5.2.2.4. Sustainability Indicators

The sustainability indicators, specifically average total CO2 production by vehicle type, are compared across alternatives as follows in Table 0.9.

Table 0.9: CO2 Production by Vehicle Type – Second Scenario

Vehicle Type	Alternative A	Alternative B	Alternative C
Boat	21,48 M	19,34 M	19,88 M
Train	546,48 K	1,18 M	1,00 M
Truck	39,73 M	26,52 M	33,82 M

5.2.3. Conclusions on the Impact of the Second Scenario on Supply Chain Performance

This scenario simulation results reveal critical insights into the performance and efficiency of the supply chain under various alternatives. The same four areas, as previously, will provide a comprehensive understanding of the impacts and effectiveness of each alternative in managing supply chain scenarios.

5.2.3.1. Alternative A

One of the primary advantages of Alternative A is its ability to maintain high service levels across all customer groups. However, it faces challenges in sustaining the same level for product C. The backlog levels remain moderate across all facilities, indicating a balanced supply chain with manageable operational challenges.

Despite these advantages, Alternative A has several significant disadvantages. It incurs substantial transportation and inventory costs, the highest among all alternatives considered. Furthermore, this alternative results in considerable CO2 emissions, especially from trucks, which produce 39.73 tCO2, and boats, which contribute 21.48 tCO2. It is the alternative with the highest emissions overall.

In summary, while Alternative A ensures high service levels, it is associated with considerable costs and environmental impact, making it less favourable when considering economic and ecological sustainability.

5.2.3.2. Alternative B

One of the primary advantages of Alternative B is its significant cost savings. It has the lowest costs across transportation and inventory, with transportation costs at 53.73 million rmu and inventory costs at 60.16 million rmu. Additionally, this alternative shows the lowest CO2 emissions, particularly from boats and trucks, highlighting its environmental benefits.

However, there are notable disadvantages associated with Alternative B. There is a noticeable drop in service levels across customer groups and products compared to Alternatives A and C. Furthermore, facilities like Barcelona and Madrid experience a significant backlog, indicating potential bottlenecks and operational inefficiencies.

In summary, Alternative B achieves cost efficiency and reduces environmental impact, leading to decreased service levels and increased backlog in some facilities.

5.2.3.3. Alternative C

One of the main advantages of Alternative C is its high service levels across all customer groups for products A and B, and it has the highest service level for product C compared to the other alternatives. Additionally, the backlog for this alternative is moderate for all customer groups, indicating a well-managed supply chain.

Anyhow, there are some disadvantages associated with Alternative C. Although it does not have the lowest CO_2 emissions, it remains lower compared to Alternative A. The costs associated with this alternative are moderate, presenting values superior to Alternative B but lower than Alternative A.

Overall, Alternative C presents the best combination of service levels and costs, offering a more balanced approach than Alternatives A and B. Strategic interventions to enhance service levels without escalating costs are necessary, particularly for Product C.

5.2.3.4. Overall Insights

The simulation results highlight key areas for improvement across the different alternatives:

I. Service Levels: Alternative A excels in service but at a high cost and emissions, while Alternative B shows a significant drop in service levels. Alternative C, however, provides a balanced service level that is better than B but not as high as A for most products. Notably, Alternative C outperforms Alternative A in service levels for Product C, highlighting its effectiveness in certain areas.

II. Costs: Cost efficiency is best achieved in Alternative B, but operational inefficiencies must be addressed to avoid service-level compromises. Alternative C presents moderate costs, offering a balanced approach between cost and service levels.

III. Sustainability: Alternative B is the most sustainable, demonstrating the feasibility of reducing CO_2 emissions while managing costs, though service levels need enhancement. Alternative C also shows moderate CO_2 emissions, balancing environmental impact with operational efficiency

By balancing all these variables, the insights reveal that while cost and sustainability are important, service quality should not be overlooked. It depends on the decision-maker's goals which alternative to choose, depending on whether the preference is to prioritise service levels, sustainability factors, or cost reduction. Overall, Alternative C presents the best combination of service levels and costs. Successful supply chain management will require a comprehensive approach covering cost efficiency, sustainability, and excellent service levels.

6. Conclusion and future work

This chapter describes the conclusions reached because of the work completed throughout this dissertation. In addition to showcasing the contributions made by this study and determining if the initially outlined objectives were met, some proposals for future work are presented.

6.1. Conclusions

This dissertation developed a new simulation-based approach to support decision-making for designing and managing multimodal transportation within supply chains, aiming to enhance their flexibility, resilience, and sustainability.

The developed approach has proven effective in meeting the primary goals defined for the research: i) understanding supply chain behaviour under different operational alternatives, ii) identifying supply chain vulnerabilities during different scenarios, and iii) quantifying the impacts and consequences of scenarios.

This research contributes to the body of knowledge in supply chain management by offering innovative solutions that enhance the resilience and sustainability of multimodal transportation networks. The findings align with and extend the current literature, providing empirical evidence and practical strategies for improving supply chain performance. The simulation model developed in this dissertation is a valuable tool for supply chain managers and policymakers to evaluate and optimise their logistics strategies under various conditions.

Assessing several operating scenarios and alternatives offered complete insights into the trade-offs between service levels, costs, and sustainability. The findings suggest that balancing these variables is critical for optimal supply chain performance. The study reveals that no single alternative is universally preferable; instead, the choice is determined by the decision-makers individual aims and priorities, such as service quality, cost efficiency, or sustainability.

However, this study is not without limitations. One notable limitation is the averaging of values from 20 simulations. In contrast, a more robust would ideally average results from a larger number of simulation runs to account for variability and ensure statistical significance. Future research should address this limitation by increasing the number of simulation runs to validate the findings more comprehensively.

Although the model was developed for the specific context of multimodal transportation and supply chain resilience, it can be generalised and adapted to other industrial sectors. This generalisation will be explored in future developments of the work.

6.2. Future Work

While this dissertation has addressed key research objectives and provided valuable insights, several areas warrant further investigation.

Firstly, the expansion of scenarios could be explored in future research. By investigating additional scenarios, including those with different geographical focuses or varying levels of market demand, a more comprehensive analysis of supply chain strategies can be achieved. This would provide deeper insights into how different conditions affect supply chain performance and resilience.

Secondly, examining the long-term sustainability impacts of multimodal transport strategies is crucial. This includes considering factors such as resource depletion, social equity, and economic viability over extended periods. Understanding these long-term impacts can help in developing strategies that are not only effective in the short term but also sustainable in the long run.

Furthermore, analyzing the role of policy and regulatory frameworks in promoting sustainable and resilient supply chain practices is important. Research should focus on how these frameworks can be optimized to support industry adoption and what specific policies are most effective in encouraging sustainable practices.

Lastly, conducting real-world implementation and case studies to validate the simulation model and strategies proposed in this dissertation is essential. These studies will ensure the practical applicability and effectiveness of the proposed strategies in diverse industrial contexts. By applying the model to real-world scenarios, researchers can identify potential improvements and refine the strategies to better meet the needs of various industries.

By addressing these areas, future research can build upon the findings of this dissertation, further advancing the field of supply chain management and contributing to the development of more resilient, efficient, and sustainable supply chains.

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Sustainable Development Goals

This chapter reflects on how the research conducted in this dissertation contributes to the United Nations Sustainable Development Goals (SDGs). This dissertation supports several key SDGs by enhancing multimodal supply chain resilience, flexibility, and sustainability through advanced simulation techniques.

I. SDG 9: Industry, Innovation, and Infrastructure

This dissertation contributes significantly to SDG 9, which aims to build resilient infrastructure, promote inclusive and sustainable industrialisation, and foster innovation. This work promotes innovation in supply chain management practices by developing a simulation-based approach to enhance the flexibility, resilience, and sustainability of multimodal transportation within supply chains. Integrating Discrete Event Simulation (DES) and Agent-Based Simulation (ABS) methods provides a novel approach to understanding and optimising complex supply chain networks, which is critical for sustainable industrial development.

II. SDG 12: Responsible Consumption and Production

SDG 12 focuses on ensuring sustainable consumption and production patterns. This research contributes to this goal by identifying vulnerabilities in supply. This helps optimise resource use, reduce waste, and improve the efficiency of transportation networks. The emphasis on sustainable practices within supply chains aligns with responsible consumption and production principles.

III. SDG 13: Climate Action

Finally, this dissertation aligns with SDG 13, which calls for urgent action to combat climate change and its impacts. By incorporating sustainable practices and advanced technologies in supply chain management, this work aims to reduce the carbon footprint of transportation networks. The focus on CO2 emissions and the promotion of green logistics practices directly contribute to climate action efforts, helping mitigate the environmental impact of supply chains.

APPENDIX A: Assumptions and Parameters for Case Study

A.1. Customers Demand

Table A.1: Customer Demand by Region

Customer	Product	Demand Type	First Occurrence	Order Interval (days)	Quantity
Portugal North	A	Periodic Demand	First Day	Normal(2;7)	Normal(15;63)
Portugal North	B	Periodic Demand	First Day	Normal(1;10)	Normal(10;49)
Portugal South	A	Periodic Demand	First Day	Normal(2;7)	Normal(15;63)
Portugal South	B	Periodic Demand	First Day	Normal(1;10)	Normal(10;49)
Spain North	A	Periodic Demand	First Day	Normal(1;5)	Normal(15;83)
Spain North	B	Periodic Demand	First Day	Normal(1;8)	Normal(12;60)
Spain Center	A	Periodic Demand	First Day	Normal(1;5)	Normal(15;83)
Spain Center	B	Periodic Demand	First Day	Normal(1;8)	Normal(12;60)
Spain South	A	Periodic Demand	First Day	Normal(1;5)	Normal(15;83)
Spain South	B	Periodic Demand	First Day	Normal(1;8)	Normal(12;60)

A.2. Inventory Policies

Table A.2: Inventory Policy by Facility

Facility	Product	Inventory Policy	Check Period (days)
Ports	All Products	Regular Safety Stock	30
Platforms	All Products	Regular Safety Stock	30
Distribution Centers	All Products	Max-Min	1

A.3. Transportation Modes

Table A.3: Transportation Modes

Vehicle Type	Capacity (m³)	Speed (Km/h)
Boat	3320	37
Train	90	80
Truck	1660	75

A.4. Transportation Time

Table A.4: Transportation Time by Path

From	To	Distance (Km)	Transportation Time (day)	Vehicle Type
Suppliers	Ports	8545,92	Normal(17.09, 0.8545)	Boat
Porto de Leixões	Chaves	120	Normal(0.24, 0.048)	Truck
Porto Sines	Entroncamento	170	Normal(0.34, 0.068)	Truck
DC's	Customers	462	Normal(0.92, 0.184)	Truck
Porto Leixões	Entroncamento	195	Normal(0.658, 0.0658)	Train
Porto Sines	Badajoz	183	Normal(1.21, 0.121)	Train
Porto Leixões	Badajoz	300	Normal(0.87, 0.087)	Train
Badajoz	Madrid	329	Normal(0.70, 0.07)	Train
Badajoz	Zaragoza	605	Normal(1.02, 0.102)	Train
Zaragoza	Barcelona	260	Normal(0.868, 0.1736)	Truck
Porto Haropa	Zaragoza	876	Normal(1.834, 0.1834)	Train
Porto Sines	Chaves	435	Normal(1.82, 0.364)	Truck
Porto Sines	Gibraltar	350	Normal(0.279, 0.0279)	Truck
Porto Sines	Madrid	512	Normal(0.261, 0.0261)	Truck
Porto Leixões	Madrid	434	Normal(0.429, 0.0429)	Truck
Porto Leixões	Barcelona	917	Normal(0.371, 0.0371)	Truck
Porto Haropa	Barcelona	910	Normal(1.251, 0.1251)	Truck

A.5. Shipping Policies

Table A.5: Shipping Policies by Vehicle Type

Vehicle Type	Policy Type	Parameters	Priority	Days of week	Start Time	End Time
Boat	FTL	Min load ratio: 0,7	FIFO	Everyday	12:00 AM	11:59 PM
Train	FTL	Min load ratio: 0,6	FIFO	Everyday	06:00 AM	11:59 PM
Truck	FTL	Min load ratio: 0,5	FIFO	Everyday	12:00 AM	11:59 PM

A.6. Sourcing Policies

Table A.6: Sourcing Policies by Delivery Destinations

Delivery Destination	Type
Ports	Uniform Split
Platforms	Uniform Split
DC's	Fastest (Dynamic Sources)

A.7. Cost per Km and CO2 Consumption

Table A.7: Cost and CO2 Consumption per Km and by Vehicle Type

Vehicle Type	Cost Calculation (rmu)	CO2 Consumption (tCO2)
Boat	0.005 * product (m^3) * distance	0.004 * product (m^3) * distance
Train	0.005 * product (m^3) * distance	0.008 * product (m^3) * distance
Truck	0.055 * product (m^3) * distance	0.06 * product (m^3) * distance

APPENDIX B: Assumptions and Parameters for the First Scenario

B.1. Customer Demand

Table B.1: Customer Demand by Region - First Scenario

Customer	Product	Demand Type	First Occurrence	Order Interval (days)	Quantity
Portugal North	A	Periodic Demand	First Day	Normal(1.8;6.3)	Normal(18;75.6)
Portugal North	B	Periodic Demand	First Day	Normal(0.9; 9)	Normal(12;58.8)
Portugal South	A	Periodic Demand	First Day	Normal(1.8;6.3)	Normal(18;75.6)
Portugal South	B	Periodic Demand	First Day	Normal(0.9; 9)	Normal(12;58.8)
Spain North	A	Periodic Demand	First Day	Normal(0.9;4.5)	Normal(18;99.6)
Spain North	B	Periodic Demand	First Day	Normal(0.9;7.2)	Normal(14.4;72)
Spain Center	A	Periodic Demand	First Day	Normal(0.9;4.5)	Normal(18;99.6)
Spain Center	B	Periodic Demand	First Day	Normal(0.9;7.2)	Normal(14.4;72)
Spain South	A	Periodic Demand	First Day	Normal(0.9;4.5)	Normal(18;99.6)
Spain South	B	Periodic Demand	First Day	Normal(0.9; 7.2)	Normal(0.9;7.2)

B.2. Cost per Km and CO2 Consumption

Table B.2: Cost and CO2 Consumption per Km per Vehicle Type - First Scenario

Vehicle Type	Cost Calculation (rmu)	CO2 Consumption (tCO2)
Boat	0.00575 * product (m^3) * distance	0.004 * product (m^3) * distance
Train	0.00575 * product (m^3) * distance	0.008 * product (m^3) * distance
Truck	0.06325 * product (m^3) * distance	0.06 * product (m^3) * distance

APPENDIX C: Assumptions and Parameters for the Second Scenario

C.1. Customer Demand

Table C.1: Customer Demand by Spain Regions - Second Scenario

Customer	Product	Demand Type	First Occurrence	Order Interval (days)	Quantity
Spain North	C	Periodic Demand	First Day	Normal(6;18)	Normal(10;45)
Spain Center	C	Periodic Demand	First Day	Normal(6;18)	Normal(10;45)
Spain South	C	Periodic Demand	First Day	Normal(6;18)	Normal(10;45)

C.2. Transportation Time

Table C.2: Transportation Time by Path - Scenario 2

From	To	Distance (Km)	Transportation Time (day)	Vehicle Type
Suppliers	Ports	8545,92	Normal(13.672;0.6836)	Boat
Porto de Leixões	Chaves	120	Normal(0.192;0.0384)	Truck
Porto Sines	Entroncamento	170	Normal(0.272;0.0544)	Truck
DC's	Customers	462	Normal(0.736;0.1472)	Truck
Porto Leixões	Entroncamento	195	Normal(0.5264;0.05264)	Train
Porto Sines	Badajoz	183	Normal(0.968;0.0968)	Train
Porto Leixões	Badajoz	300	Normal(0.696;0.0696)	Train
Badajoz	Madrid	329	Normal(0.56;0.056)	Train
Badajoz	Zaragoza	605	Normal(0.816;0.0816)	Train
Zaragoza	Barcelona	260	Normal(0.6944;0.13888)	Truck
Porto Haropa	Zaragoza	876	Normal(1.4672;0.14672)	Train
Porto Sines	Chaves	435	Normal(1.456;0.2912)	Truck
Porto Sines	Gibraltar	350	Normal(0.2232;0.02232)	Truck
Porto Sines	Madrid	512	Normal(0.2088;0.02088)	Truck
Porto Leixões	Madrid	434	Normal(0.3432;0.03432)	Truck
Porto Leixões	Barcelona	917	Normal(0.2968;0.02968)	Truck
Porto Haropa	Barcelona	910	Normal(1.0008;0.10008)	Truck