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Towards Integrated Synchromodal Transport Planning and Container Terminal Operations: A Multi-Agent System Approach

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MSc Thesis Research

Towards Integrated Synchromodal Transport Planning and Container Terminal Operations: A Multi-Agent System Approach

by

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Preface

In front of you is the final report of my graduation research, conducted in partial fulfilment of the requirements for the Master's degree in Transport, Infrastructure, and Logistics at Delft University of Technology. This research explores the integration of synchromodal transport planning and container terminal operations using a Multi-Agent System to assess efficiency, adaptability, and cost-effectiveness in logistics networks and inland container terminals.

The process of writing this thesis has been both challenging and rewarding. It has broadened my understanding of synchromodal transport, terminal operations, and multi-agent systems, while also revealing the complexities and practical constraints of simulating real-world logistics. Furthermore, carrying out this research independently at TU Delft has been a valuable learning experience, strengthening both my academic, analytical, problem-solving, and project management abilities.

I would first like to express my gratitude to my supervisors at Delft University of Technology for their continuous support, insightful feedback, and expert guidance, which have played a crucial role in shaping this research. Their critical perspectives and encouragement have been invaluable in refining my work. I also thank my fellow students for their participation in the discussions, feedback, and shared experiences that have provided valuable support throughout the research process.

Finally, I would like to thank my friends and family for their patience, encouragement, and unwavering support throughout this process, with a special thanks to Kim for always being there for me. Their belief in me has been a constant source of motivation. I hope that this thesis contributes to ongoing research in synchromodal transport and container terminal optimisation, providing valuable information for both academia and industry.

Lars Koetsier
Delft, May 2025

Abstract

The introduction of the shipping container revolutionised global trade by significantly reducing handling costs, improving efficiency, and enabling intermodal transportation. This development paved the way for the expansion of international trade and the development of highly interconnected global supply chains. Since then, seaborne trade has grown exponentially, with more than 80% of global trade now being transported by sea and waterways. The scale of modern-day global logistics presents both opportunities and challenges, as increasing trade volumes place pressure on supply chain networks and their infrastructure, such as terminals and main ports, to remain efficient, resilient, and sustainable.

Despite significant advances in logistics, global supply chains continue to face persistent challenges. Congestion, sustainability concerns, and vulnerability to disruptions have become major obstacles, affecting industries worldwide. Recent examples of such obstacles are the COVID-19 pandemic and the blockage of the Suez Canal, both of which placed supply chains under massive pressure. Synchromodality has been identified as a potential solution for solving some of these concerns.

As a relatively new concept, synchromodality has mainly been studied at a theoretical level, focusing on its definition and potential. As the concept of synchromodality seems to gain attention from a broader public, more recent research has also focused on the more quantitative side. These quantitative studies primarily model the transport planning side of synchromodality. In these studies, some aspects in the supply chain have been overlooked so far, mainly the impact on infrastructure such as container terminals. These nodes play a critical role as they facilitate the transshipment options between different modes of transportation.

This research focuses on addressing this overlooked area in the existing academic landscape. Aspects such as the loading, unloading and stacking of containers are explicitly modelled in combination with synchromodal transport planning optimisation. This allows for an assessment of how synchromodality influences container terminal operations and how constraints and the dynamics at container terminals, such as congestion, influence the transport planning. This approach is expressed in the following research question:

How does the integration of synchromodal transport planning and container terminal operations impact the efficiency of terminal operations, the adaptability of transport planning, and the overall cost-effectiveness of supply chain operations?

To answer this question, this research develops a model that is inherently characterised by synchromodality. Throughout this model, its key characteristics – flexible mode selection, real-time data exchange, cost and time optimisation, environmental sustainability, collaboration across stakeholders and infrastructure adaptations – are accounted for. A multi-agent system is used as a framework for this model, as this presents a good option to model the different stakeholders involved in synchromodal transport. In this research two types of agents are considered: a planning agent, which is the core of synchromodal decision-making, and a terminal agent, which is used to model the terminal operations.

The planning agent is represented by the synchromodal transport planning problem with flexible services. This model provides an extensive optimisation heuristic that generates a synchromodal transport plan. The container terminal is represented by a stacking problem optimisation model; this model is able to perform the basic operations at a terminal in regard to container handling. The orchestration of the multi-agent systems, which includes the interactions and coordination between the two types of agents, is designed based on a fifth-party logistics structure. This structure is designed to facilitate synchromodality and aims to centralise and streamline decision-making and information flows from the stakeholders. For this research this structure helps with ensuring that the multi-agent system keeps a synchromodal nature as well as simplifying the technical requirements.

The development of the multi-agent system was conducted over a number of steps. With the first steps primarily focusing on adapting the models selected as representations of the agents so that they can share and receive information from each other. The next step focused on the planning agent to create a transport plan, after which the terminal agents performed a feasibility check. This feasibility check consisted of comparing the observed service times of vehicles at terminals compared to the scheduled service times in the transport plan. The final step focused on developing an iterative feedback loop between the planning and terminal agents. This feedback loop should allow for the planning agent to create a more feasible transport plan.

After the development of the multi-agent system was completed, its performance was analysed on performance metrics, including container relocation frequency, dwell times, and cost efficiency. The findings indicate that the integration of synchromodal transport planning with container terminal operations yields several significant improvements. The iterative feedback loop between the transport planning agent and terminal agents facilitates better-informed decision-making, leading to feasible transport planning and improved resource utilisation.

Scenario analysis yielded further interesting results in terms of how a synchromodal planner would adapt to disruptions and what effect these could have on container terminals. The two most interesting findings are a decrease in the number of transshipments and a modal shift towards the faster, more flexible, but also more expensive, more polluting transport modes. These findings still hold under the examined force majeure conditions where the consignee is more lenient towards a delay due to a disruption. However, these lenient conditions do seemingly allow for the synchromodal planner to have more flexibility and be less dependent on the fast and flexible modes.

The effectiveness of the model is, however, partially constrained by data availability, as real-world shipment and infrastructure data were not fully integrated into the simulation. Furthermore, computational scalability presents a challenge, particularly as the number of agents and interactions increases, which may result in longer processing times. The model further functions based on specific assumptions, including a singular planning agent, optimal agent collaboration, and streamlined congestion dynamics, which may need further refinement in further research.

In conclusion, this research demonstrates that the integration of synchromodal transport planning and container terminal operations improves the efficiency and adaptability of synchromodal logistics networks. The multi-agent system successfully illustrates dynamic responses to congestions and disruptions and improved operational performance for both planners and container terminals. This research enhances the planning of synchromodal transport and the optimisation of container terminals, providing valuable insights for both academic and industrial applications.

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List of Abbreviations

3PL . . . Third-Party Logistics
4PL . . . Fourth-Party Logistics
5PL . . . Fifth-Party Logistics
AGV . . . Automated Guided Vehicle
ALNS . . . Adaptive Large Neighborhood Search
BRP . . . Block Relocation Problem
BCTN . . . Barge Container Terminal Netherlands
BTT . . . Barge Terminal Tilburg
CTT . . . Combi Terminal Twente
CRP . . . Container Relocation Problem
DCRP . . . Dynamic Container Relocation Problem
EEA . . . European Environment Agency
FMaaS . . . Freight Mobility as a Service
FMC . . . Fixed-Maximal Configuration
MAS . . . Multi-Agent System
MDP . . . Markov Decision Process
MILP . . . Mixed Integer Linear Programming
PDPT . . . Pickup and Delivery Problem with Transshipment
PSLP . . . Parallel Stack Loading Problem
RL . . . Reinforcement Learning
SAC . . . Size-Adapted Configuration
SP . . . Stacking Problem
STM . . . Service Time Matrix
STPP . . . Synchromodal Transport Planning Problem
STPP-FS . . . Synchromodal Transport Planning Problem with Flexible Services
UNCTAD . . . United Nations Conference on Trade and Development
VRP . . . Vehicle Routing Problem

1
Introduction

1.1. Context and Background

In 1956, the American entrepreneur Malcolm Purcell McLean developed a metal box that would change the landscape of global goods and logistics (Mayo & Nohria, 2005). The intermodal shipping container revolutionised global trade by reducing shipping costs, increasing efficiency, and enabling intermodal transportation. This innovation paved the way for the rapid expansion of international trade and the growth of global supply chains. McLean's innovations revolutionised the shipping industry, cutting overall costs by 25 percent and propelling his company, SeaLand Industries, to become the world's leading cargo shipping business (Mayo & Nohria, 2005).

Since then, global trade has experienced significant growth throughout the twentieth and twenty-first centuries, with seaborne trade constituting the majority of this expansion. The United Nations Conference on Trade and Development (UNCTAD) reports that trade in products in 2024 exceeds 100 times that in 1964, with over 80% of world trade conducted via maritime transport (UNCTAD, 2021, 2024a). As global and seaborne trade continues to expand, markets are becoming increasingly interconnected, presenting both new opportunities and substantial challenges for industries worldwide. This increased interdependence, driven by globalisation, underscores the need for innovative solutions to address complex logistical and operational inefficiencies. Understanding and optimising these systems is more critical than ever to ensure that goods move seamlessly across borders and reach their destinations in a timely and cost-effective manner. Specific challenges for the logistics industry are sustainability concerns, congestion, and susceptibility to disruptions. Recent examples of such disruptions include the COVID-19 pandemic, which led to a peak 306% increase in global freight rates in 2021 compared to 2019, and the blockage of the Suez Canal, through which 22% of global container traffic passes, by the Ever Given Taiwanese vessel (Pulido, 2023; Russon, 2021; UNCTAD, 2024b).

A compelling solution to improve the flow of goods in a more sustainable and resilient manner is the concept of synchromodality. Synchromodality, which involves the seamless integration and optimisation of multiple modes of transport within a supply chain, has the potential to revolutionise logistics by addressing long-standing challenges and reducing the reliance on unimodal transport in the hinterland (Tavasszy et al., 2017). However, despite its potential, synchromodality remains largely unknown in the European Union and beyond, with recognition limited primarily to the Benelux countries (Pfoser et al., 2016). In 2022, the European Environment Agency (EEA) briefly acknowledged the advantages of synchromodality in its report on transport and the environment (European Environment Agency, 2022). However, subsequent references to synchromodality from the European Union have again predominantly originated from Benelux initiatives (DIWA, 2022; European Commission - Directorate General for Mobility and Transport, 2016). Synchromodality is a relatively new concept that has mainly been studied at the conceptual level. Although technical and quantitative studies have focused on planning and optimisation, aspects related to its impact on infrastructure, such as container terminal operations, remain underexplored.

Container terminals serve as critical nodes within logistics networks, facilitating the transfer of goods between various transport modes. However, persistent congestion and limited operational efficiency at many container terminals disrupt the flow of goods, extend delivery times, and increase operational costs. External factors, such as the aftermath of the COVID-19 pandemic and the ongoing conflict between Russia and Ukraine, have further exacerbated congestion problems, adding to these challenges (International Monetary Fund, 2022; NOS, 2022). The successful adoption of synchromodality could require more frequent modal shifts, leading to an increased volume of container movements within container yards. An article in Koh and Koc (2022) highlights the severe container congestion at the Port of Rotterdam and several other European ports, largely due to an excessive number of empty containers stranded in Europe. These reports raise a valid question about the feasibility of implementing synchromodality and introducing more container movements in container yards under these congested circumstances.

1.2. Research Objectives and Scope

Synchromodality has shown promise in addressing logistics challenges, but further quantitative exploration is needed. Research from Delft University of Technology (TU Delft) on Freight Mobility as a Service (FMaaS) aims to move beyond current digital freight platforms, which focus mainly on road transport planning and booking. FMaaS seeks to offer a real-time synchromodal matching service that provides a more sustainable alternative, enhancing the dynamic efficiency of the Dutch multimodal freight network while supporting national environmental goals. The project aims to develop a platform that is both attractive and acceptable to all stakeholders, prioritising sustainable choices (Delft University of Technology, 2024; Dutch Research Agenda (NWA-ORC), 2021). Six research layers have been identified within the project, that are utilised to help shape this research.

- "From a business perspective, we need to understand how the modus operandi of the different stakeholders will be disrupted and define the new business models" (Delft University of Technology, 2024; Dutch Research Agenda (NWA-ORC), 2021).
- "New operational problems need to be tackled and optimized, and new strategies need to be defined to cope with the unpredictability of the system" (Delft University of Technology, 2024; Dutch Research Agenda (NWA-ORC), 2021).
- "Our legal framework should tackle problems of liability, and regulations and prevent the risk of abuse of power by the (big) players" (Delft University of Technology, 2024; Dutch Research Agenda (NWA-ORC), 2021).
- "We need to incentivize the shippers to take a primary role in the usage of the platform and the transport providers to fully adopt FMaaS" (Delft University of Technology, 2024; Dutch Research Agenda (NWA-ORC), 2021).
- "The data management is crucial to foster collaboration and trust in the platform" (Delft University of Technology, 2024; Dutch Research Agenda (NWA-ORC), 2021).
- "Algorithms and IT for dynamic and responsive environments aimed at achieving sustainable choices" (Delft University of Technology, 2024; Dutch Research Agenda (NWA-ORC), 2021).

The objective of this research aligns with the identified research layers of the FMaaS project. It primarily aims to provide insights into the feasibility of synchromodality from a business perspective, as well as to explore new operational problems focusing on container terminals. To achieve this synchromodal container stacking objective, recent developments in synchromodal studies are used to represent a synchromodal network, enabling an assessment of its impact on container terminals. The project will address operational problems such as optimising container placement to minimise total movements and reducing dwell times, as well as exploring the internal dynamics between the synchromodal transport planning and terminal agents. The emphasis will be on understanding the potential challenges and benefits of synchromodality for both terminal efficiency and business outcomes.

1.3. Research Questions and Approach

The main research question focuses on leveraging existing knowledge of synchromodal transport planning models and container stacking optimisation models to assess the impact of synchromodality on container terminals and the feasibility of its implementation. The sub-research questions of this research are structured keeping the research layers from the FMaaS project in mind. The main research question is stated below with the sub-research questions that will help to answer the main research question shown in Table 1.1.

"How does the integration of synchromodal transport planning and container terminal operations impact the efficiency of terminal operations, the adaptability of transport planning, and the overall cost-effectiveness of supply chain operations?"

Table 1.1: Sub-research questions

	Sub-research question
SQ.1	What are the key characteristics of synchromodality, and how do its complexities shape the integration of transport planning and container terminal operations?
SQ.2	How can interactions between transport planners and terminal operators be modelled to simulate decision-making, coordination, and real-time adaptability in synchromodal transport?
SQ.3	What real-world scenarios can be used to evaluate how the integration of synchromodal transport planning and container terminal operations impacts terminal efficiency, transport adaptability, and supply chain cost-effectiveness?

The research begins with a review of a literature that focuses on synchromodality, synchromodal transport planning, and container stacking. This review will address SQ.1 by identifying key characteristics of synchromodality that should be included in the research and help shape the integration of synchromodality and container terminal operations. The outcome of SQ.1, together with an extended review of the literature on stakeholders in synchromodal transport and their interactions, will help the design of the model in SQ.2.

The remainder of SQ.2 focuses on the development of a model that can be used to assess the integration of synchromodal transport planning and container terminal operations. This is put to extensive testing and analysis to further optimise the model and derive key findings on the integration, which will help answer the main research question. With the developed model it is possible to continue to SQ.3 which will focus on real-world scenarios, such as disruptions, to further analyse the effects on the integration of synchromodality and container terminal operations.

1.4. Research Relevance

This research is expected to be relevant in the context of modern logistics and supply chain management, as it addresses the key challenges facing container terminals in a rapidly evolving global trade environment. With the increasing interconnection of global markets and the growing complexity of transportation networks, optimising container terminal operations has become crucial to improve efficiency, reduce costs, and improve sustainability. The use of synchromodality, which smoothly integrates several transport modes, presents a promising resolution to these difficulties.

This research examines the viability of synchromodal transport planning and container stacking optimisation within a multi-agent framework, offering significant insights into this unique concept. The results could substantially contribute to the development of more efficient, resilient, and sustainable container terminal operations, ultimately benefiting stakeholders in the logistics and transportation sectors. In addition, the findings could inform policy decisions, operational strategies, and technological advances, fostering greater collaboration and optimisation across the supply chain. The integration of business, operational, data management, and algorithmic factors in this research ensures its broad relevance to both academia and industry, offering actionable insights to advance the state of logistics.

1.5. Research Outline

This research is structured as follows: Chapter 2: Literature Review presents a thorough examination of the current literature about synchromodal transport and container stacking optimisation. It underscores essential theories, methodology, and research deficiencies, establishing the groundwork for the research.

Chapter 3: Research Methodology offers comprehensive descriptions of the research design, chosen models and adaptations, data sources and needs, experimental setup and development process, as well as constraints and assumptions. A comprehensive account of the methodological selections is presented to facilitate an evaluation of the validity and dependability of the research findings.

Chapter 4: Model Development presents the technical development of the framework and models used in this research. The emphasis is on three primary elements: the depiction of synchromodality inside the framework, the portrayal of container terminal activities within the framework, and the fundamental architecture and technological orchestration of the framework itself.

Chapter 5: Results & Analysis presents the results and the conducted tests and analysis. These will focus on the computational impact and performance of the models and adaptations, the overall performance of the integration of synchromodality and container terminal operations, and finally the results and the real-world scenario analysis.

Chapter 6: Discussion interprets the important findings in connection to the research aims and existing literature. The text examines managerial ideas, practical ramifications, strengths, contributions of the research, and acknowledges its limitations. Ultimately, it delineates recommendations and pathways for subsequent research.

Chapter 7: Conclusion summarises key research findings, assesses the fulfilment of research objectives, and provides recommendations for future research and the practical application of synchromodal transport models. It examines how the results enhance both theoretical and practical developments in synchromodal transport and container stacking optimisation.

2

Literature Review

This chapter presents the review of the literature for this research. The first section details the procedure for searching relevant papers. The second section visualises the bibliometric network, mapped using VOSviewer software to explore the scientific landscape. Together with a thematic overview of the relevant literature in section three, this provides the basis for identifying the research gap in section four. Finally, the fifth and sixth sections discuss the theoretical framework and provide an overview of the literature review.

2.1. Search Procedure

Table 2.1 presents the results of the search process. The process commenced with a series of keywords employed as search queries in Scopus and Web of Science. For each query, the search terms, date, database utilised, total hits, and results were documented. Results were ranked according to citation count, prioritising recent and highly cited publications. Relevant notes, including highlighted papers, were incorporated as necessary.

Initial search terms focused on synchromodality itself, highlighting papers that describe its concept, potential, challenges, or modelling. Then the focus moved towards container terminal operations and relocation optimisation. The findings of this search led to a new search area that focused on reinforcement learning, which is applied to aspects both concerned with modelling synchromodal transport and container terminal operations. The final part of the search procedure focused on the future development of ports and container terminals together with aspects of concern that were mentioned in earlier papers, such as carbon credits for emissions concerns, demurrage and detention concerns, and the development of ultra-large container vessels (ULCV).

Table 2.1: Search procedure and results.

Search term	Database [# Hits]	Highlighted Papers
Synchromodal OR Synchromodality	Scopus [143] Web of Science [125]	Van Riessen et al. (2015); Pfoser et al. (2016); Tavasszy et al. (2017); Giusti et al. (2019)
(Synchromodality OR Synchromodal) AND Container Stacking	Scopus [0] Web of Science [0]	-
(Synchromodality OR Synchromodal) AND Optimisation	Scopus [35] Web of Science [40]	Y. Zhang et al. (2021); Y. Zhang et al. (2022a)
(Synchromodality OR Synchromodal) AND Container and Terminal	Scopus [12] Web of Science [12]	M. Zhang and Pel (2016); Guo et al. (2020); Zweers et al. (2020)
(Synchromodality OR Synchromodal) AND Container and Operations	Scopus [14] Web of Science [14]	Van Riessen et al. (2014)
Container AND (Reshuffling OR Reshuffle)	Scopus [121] Web of Science [91]	Murty et al. (2005); Lee et al. (2006); Han et al. (2008); L. Wang and Zhu (2019); Zhou et al. (2020)
Container AND Stack AND Optimisation	Scopus [166] Web of Science [294]	Ng and Talley (2020); Zweers et al. (2020); Feng et al. (2022); B. Jin and Tanaka (2023)
Intermodal AND Container AND Optimisation	Scopus [254] Web of Science [255]	Hao and Yue (2016); Yan et al. (2020)
Intermodal AND Terminal AND Optimisation	Scopus [230] Web of Science [214]	Zehendner and Feillet (2014); L. Wang and Zhu (2019); Muravev et al. (2021)
Reinforcement AND Learning	Scopus [119,637] Web of Science [77,113]	Mnih et al. (2015)
Reinforcement AND Learning AND Container AND Terminal	Scopus [74] Web of Science [35]	Guo et al. (2022)
Reinforcement AND Learning AND Container AND Operations	Scopus [80] Web of Science [46]	Rida et al. (2011); Fotuhi et al. (2013); Hirashima (2016); Hamdy et al. (2022); X. Jin et al. (2023)
Reinforcement AND Learning AND Container AND Stacking	Scopus [21] Web of Science [17]	Hirashima et al. (2006); Gao et al. (2023)
Reinforcement AND Learning AND (Synchromodality OR Synchromodal)	Scopus [3] Web of Science [3]	Guo et al. (2022); Rivera and Mes (2022); Y. Zhang et al. (2023)
Container AND Terminal AND (Future OR Development) AND Since 2019	Scopus [607] Web of Science [563]	Gharehgozli et al. (2019); X. Wang et al. (2020); Filom et al. (2022); Clemente et al. (2023)
Ultra AND Large AND Container AND Vessel AND Terminal	Scopus [22] Web of Science [12]	Prokopowicz and Berg-Andreassen (2016); Ge et al. (2019)
Container AND Demurrage AND Detention	Scopus [6] Web of Science [3]	Fazi and Roodbergen (2018); Storms et al. (2023)
Carbon AND Credit AND (Container OR Shipping)	Scopus [36] Web of Science [28]	Memari et al. (2021); Yuan et al. (2023)

Note: The search procedure was performed between September and November 2025; the results reflect the state of the literature at that time.

2.2. Bibliometric Network

To help structure and interpret the results of the search procedure, a bibliometric network has been created based on abstracts, keywords, and titles of relevant articles retrieved from the Web of Science, as outlined in Table 2.1. Using VOSViewer, a specialised natural language processing tool, data has been analysed to visualise relationships and thematic clusters within the literature (VOSViewer, n.d.).

The resulting bibliometric network, shown in Figure 2.1, reveals three distinct clusters, each representing different thematic focuses in the existing body of research. The blue group in the upper left comprises terms associated with synchromodality, intermodal transportation, container traffic, and transportation. The green group on the bottom left focuses on potential applications and concepts such as future developments, technological requirements, and emissions. The red cluster, located on the right, is dedicated to quantitative, algorithmic, and mathematical aspects, including topics such as algorithms, constraints, scheduling, loading, stacking, and optimisation.

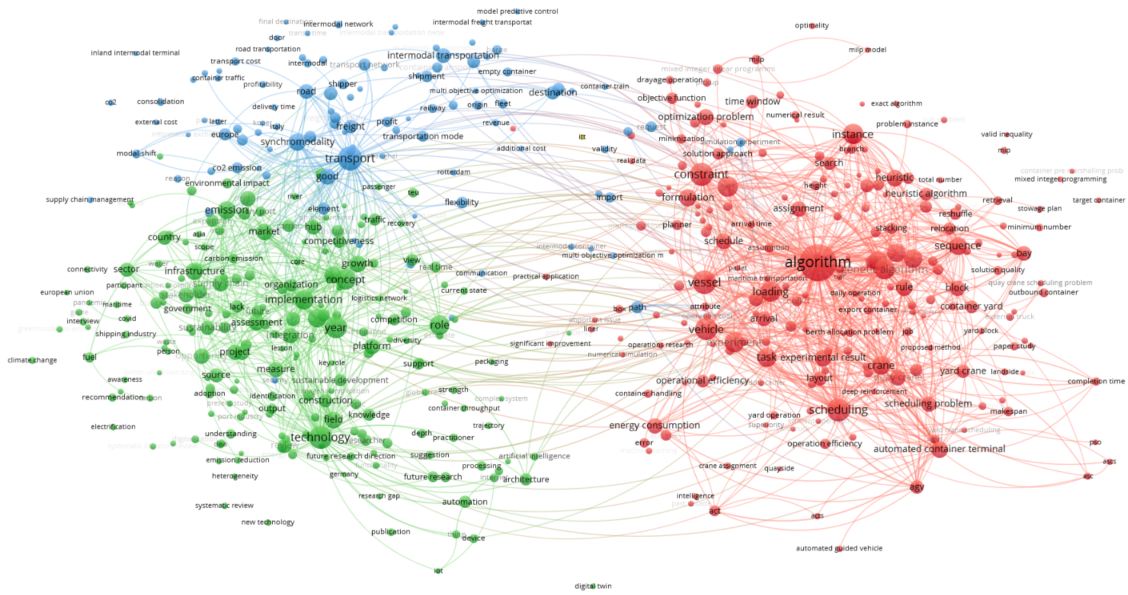


Figure 2.1: Bibliometric network.

Note. Author's creation using VOSviewer.

Focusing on the term 'Synchromodality' and its relationships within the bibliometric network in Figure 2.2, synchromodality is frequently mentioned in papers associated with the transportation-focused blue cluster and the green cluster related to technology and concepts. However, its connection to the red cluster, which focuses on quantitative and algorithmic studies, is minimal. This suggests that synchromodality has not yet been extensively studied from a mathematical or algorithmic perspective. It also stands out that synchromodality is only loosely embedded in the blue cluster. It is related to terms such as transport, modal shift, and flexibility but not directly to topics such as container terminals or stacking optimisation.

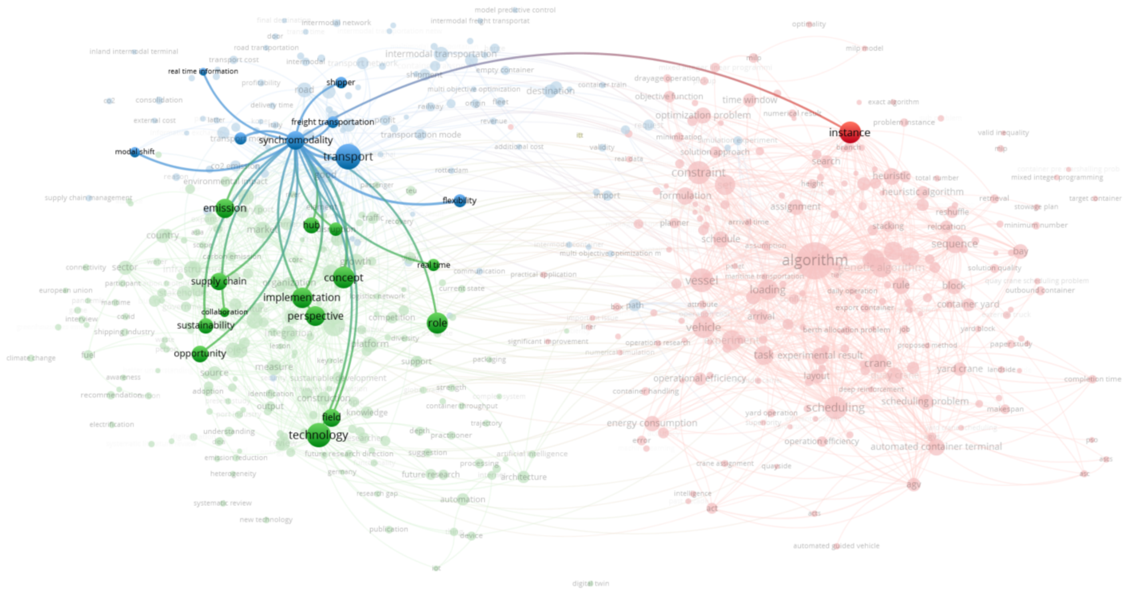


Figure 2.2: Bibliometric network: *'Synchromodality'*.

Note. Author's creation using VOSviewer.

Examining the words 'Concept' in Figure 2.3 and 'Technology' in Figure 2.4 of the green cluster reveals close links not just with the blue cluster but also with the red cluster. This suggests that the ideas of multimodal transport, automation, and transportation have been researched, with at least some investigation of algorithms in these domains.

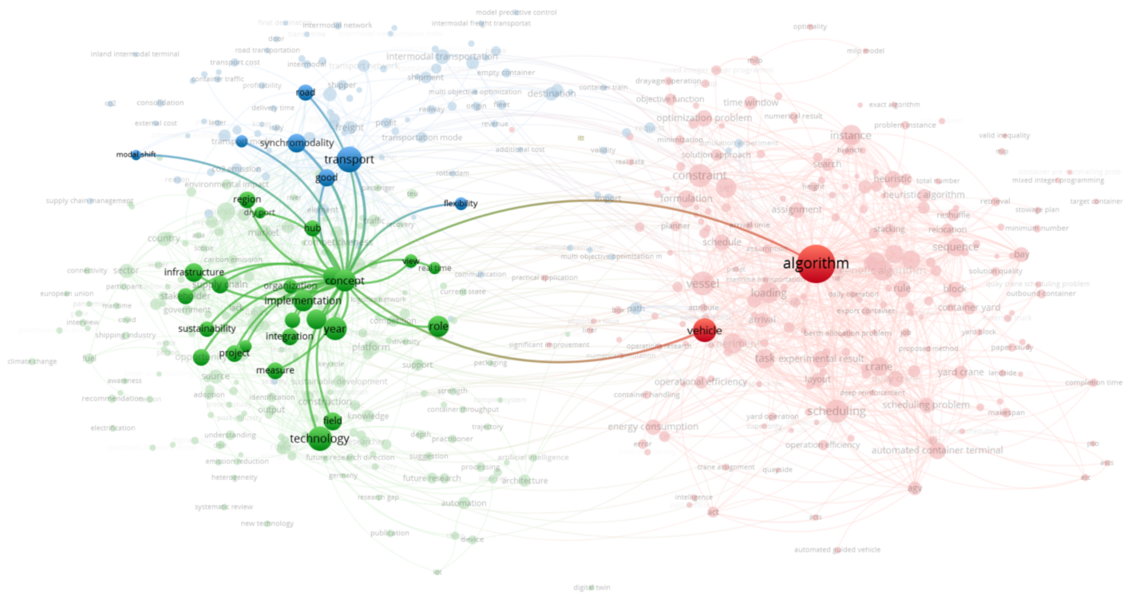


Figure 2.3: Bibliometric network: *'Concept'*.

Note. Author's creation using VOSviewer.

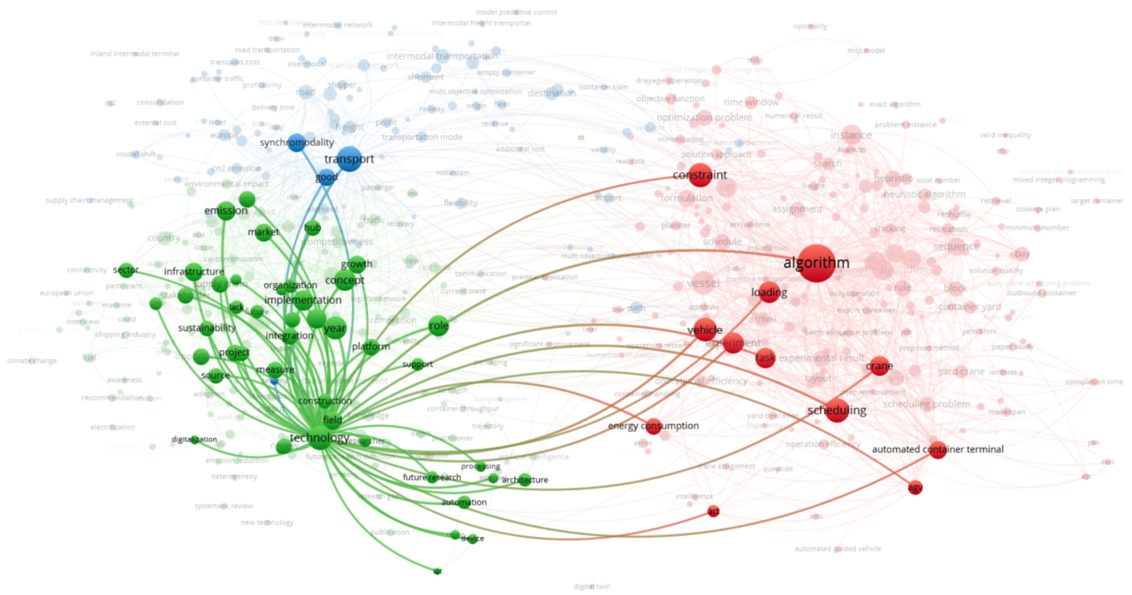


Figure 2.4: Bibliometric network: *'Technology'*.

Note. Author's creation using VOSviewer.

Looking at the red cluster through the lens of the term 'Algorithm' (Figure 2.5), strong internal connections within the cluster are observed, as well as notable links to the green and blue clusters. This indicates that quantitative algorithmic research has been utilised for both the conceptual and prospective development facets of logistics, although not explicitly for synchromodality.

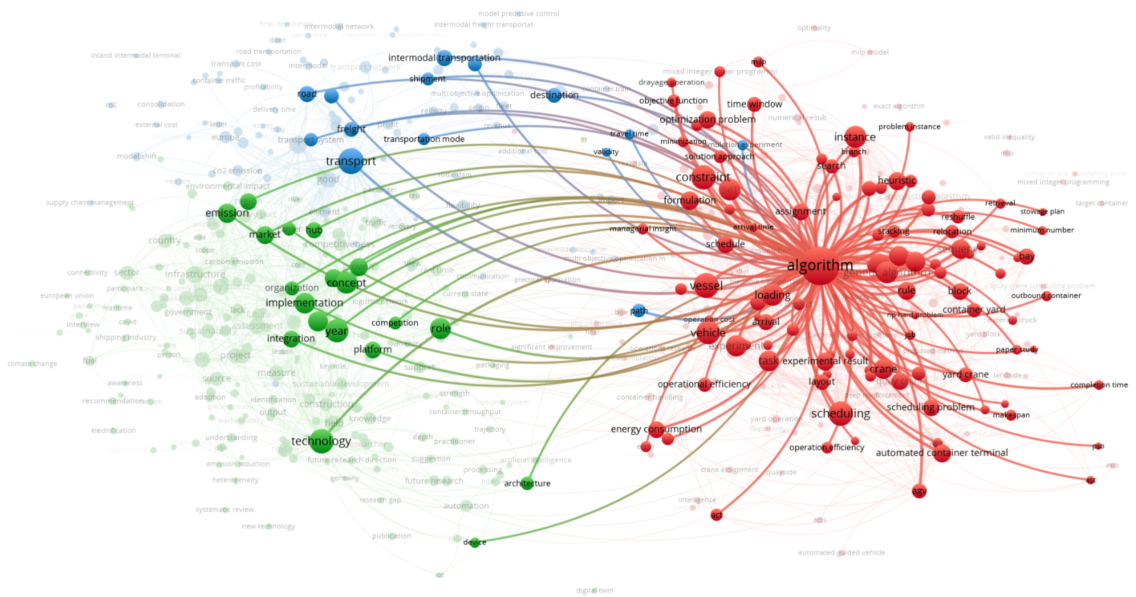


Figure 2.5: Bibliometric network: *'Algorithm'*.

Note. Author's creation using VOSviewer.

Since a great focus of this research is on synchromodality, a separate bibliographic network was created to capture research that specifically contains the terms synchromodal or synchromodality in Figure 2.6. This refined network isolates studies that focus on the core concept, facilitating a more targeted analysis of the literature. This network emphasises synchromodality, highlighting its links to essential research themes including logistics, transport mode, collaboration, and planning, which are integral to the overarching discussion on multimodal transportation systems.

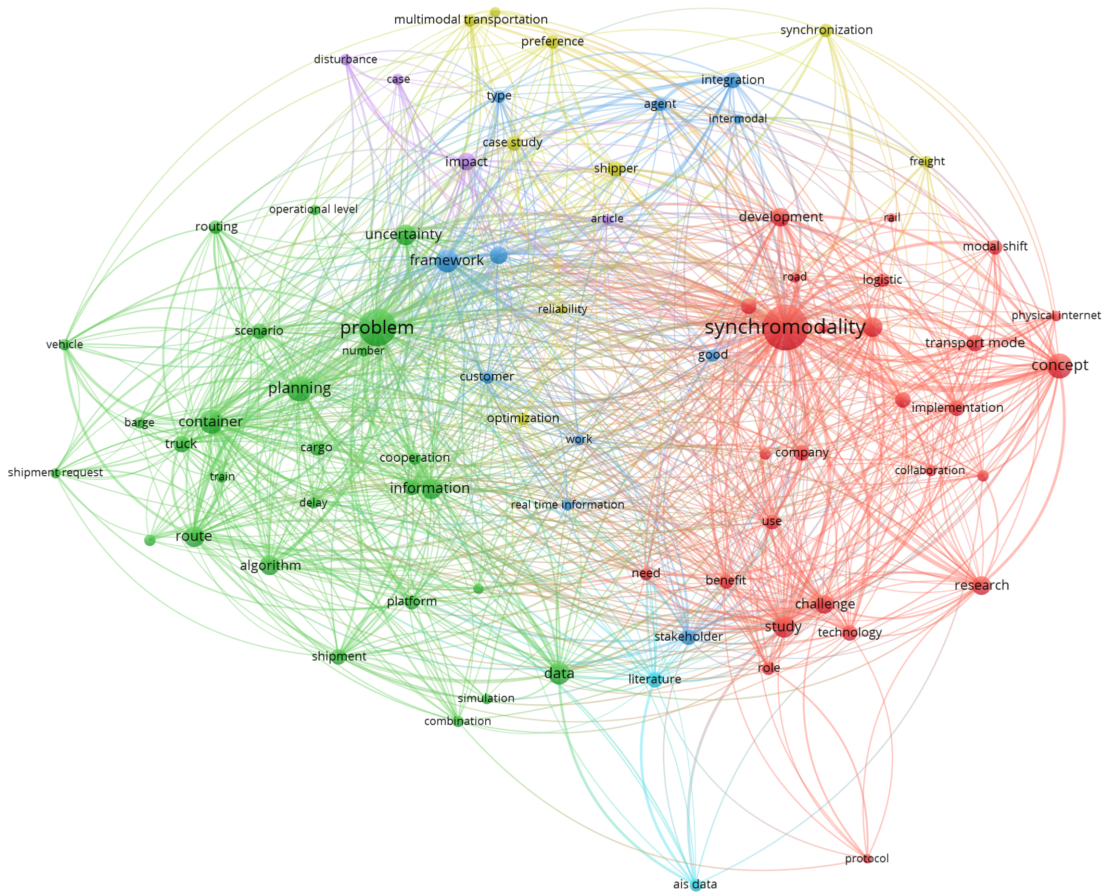


Figure 2.6: Synchromodal bibliometric network.

Note. Author's creation using VOSviewer.

Although synchromodality is a well-researched concept, there is, in fact, a limited focus on its quantitative impact. While algorithmic approaches and planning are discussed, the networks suggest that there is room to expand quantitative studies that explore operational impacts and performance improvements. This observation is supported by the relatively sparse connections between synchromodality and terms such as algorithm, data, and quantitative within the network, indicating a lack of extensive empirical studies focused on its measurable effects. Another part of the search procedure specifically focused on container terminal operations such as stacking optimisation in combination with synchromodality. Again, a similar potential gap arises, as the network does not show a clear relation between synchromodality and the container terminal operations.

2.3. Thematic Literature Review

The results of the search procedure and visualisation of the bibliometric network provide an initial indication of a potential research gap in the landscape of quantitative research on synchromodality and container terminal operations. However, these findings serve as a preliminary indication, and a more detailed and conclusive investigation of the research gap is provided through the thematic overview of the literature.

Table 2.2 provides an extensive overview of the reviewed articles, classifying them according to the concept studied, the theoretical or quantitative nature of the research, the focus of any applied optimisation, the transport modes involved, and the additional logistical aspects considered. A (✓) indicates that a topic is specifically mentioned in a paper, while a (✳) signifies that it is partially mentioned. For example, the papers are classified by modes such as deep sea, inland waterways, rail, or road. However, some papers do not specifically discuss modes; instead, they refer to services that could apply to any mode. Therefore, if a paper does not specify a mode and it could be applied to any mode, this would be marked with (✳).

The categorisation by concept focuses on whether they address intermodal transport, synchromodal transport, or terminal development. They are then classified according to their applications, such as whether they employ mathematical modelling, reinforcement learning, simulation, or primarily explore theoretical concepts. In addition, the type of optimisation is specified, if applicable, focusing on container stacking optimisation, synchromodal transport planning, terminal equipment, or loading and unloading of shipments. Finally, any specific concepts included—such as carbon credits or taxation, container shortages, demurrage and detention fees, or developments concerning ultra-large container vessels—are noted.

Table 2.2: Thematic overview of studies and main differentiators.

	Focus Area			*Application Type*				*Optimisation Focus*				*Included Modes*				*Contextual Aspects*			
	Intermodal Transport	Synchromodality	Container Terminals & Ports	Quantitative Modelling	Reinforcement Learning	Simulation	Theoretical	Container Stacking	Transport Planning	Intra-Terminal Operations	Transfer Operations	Deep Sea	Inland Waterway	Rail	Road	Carbon Credits & Sustainability	Container Shortage	Demurrage & Detention	Ultra Large Container Vessel
Clemente et al. (2023)			✓				✓					✓				✓			
Fazi and Roodbergen (2018)	✓			✓					✓			✳	✳	✳	✳			✓	
Feng et al. (2022)	✓		✳	✓				✓				✳	✳	✳	✳				
Filom et al. (2022)	✓	✳			✳		✓	✳	✳			✳	✳	✳	✳	✳		✓	
Fotuhi et al. (2013)	✓				✓			✳			✓				✓				
Gao et al. (2023)	✳		✓	✳	✳	✓		✳		✓	✳	✓	✳	✳	✓	✳			
Ge et al. (2019)			✓				✓				✳	✓							✓
Gharehgozli et al. (2019)	✓		✓				✓	✳		✳	✳	✓	✳	✳	✳	✳			✳
Giusti et al. (2019)	✓	✓					✓					✓	✓	✓	✓	✳			✳
Guo et al. (2020)	✓	✓		✓					✓			✓	✓	✓	✓	✓			
Guo et al. (2022)		✓		✓	✓				✓			✓	✓	✓	✓	✓			
Hamdy et al. (2022)			✓		✓		✓	✓				✳	✳	✳	✳				
Han et al. (2008)	✳		✓	✓				✓		✳	✓	✓							
Hao and Yue (2016)	✓			✓					✓			✓		✓	✓				
Hirashima et al. (2006)	✳		✓	✓	✓			✓			✳								
Hirashima (2016)	✳		✓	✓	✓			✳			✓			✓					
X. Jin et al. (2023)			✓	✓	✓			✓								✳			
Lee et al. (2006)			✓	✓				✓			✳								
Memari et al. (2021)				✓			✓									✓			
Mnih et al. (2015)					✓														
Muravev et al. (2021)	✳		✓	✳		✓		✳		✓	✳	✓		✓		✳		✓	
Murty et al. (2005)			✓	✓				✓		✳	✓	✓			✓				
Ng and Talley (2020)	✓		✓	✓						✳	✓			✓		✳	✳		✳
Pfoser et al. (2016)		✓					✓					✳	✳	✳	✳				
Prokopowicz and Berg-Andreassen (2016)			✓				✓					✓							✓
Rida et al. (2011)			✓		✓					✓	✓	✓							
Rivera and Mes (2022)		✓		✓	✳	✓			✓			✓	✓	✓	✓				
Storms et al. (2023)		✓					✓									✳	✳	✓	
Tavasszy et al. (2017)	✓	✓					✓					✓	✓	✓	✓				
Van Riessen et al. (2014)	✓	✓		✓							✳		✓	✓	✓				
Van Riessen et al. (2015)		✓					✓						✓	✓	✓				

	Intermodal Transport	Synchromodality	Container Terminals & Ports	Quantitative Modelling	Reinforcement Learning	Simulation	Theoretical	Container Stacking	Transport Planning	Intra-Terminal Operations	Transfer Operations	Deep Sea	Inland Waterway	Rail	Road	Carbon Credits & Sustainability	Container Shortage	Demurrage & Detention	Ultra Large Container Vessel
	Focus Area			*Application Type*				*Optimisation Focus*				*Included Modes*				*Contextual Aspects*			
L. Wang and Zhu (2019)	✓		✓	✓				✳			✓			✓	✓	✳			
X. Wang et al. (2020)			✓				✓									✳			
Yan et al. (2020)	✓			✓				✳			✓	✓		✓					
Yuan et al. (2023)				✓			✓		✳			✓				✓			
Zehendner and Feillet (2014)	✓		✓	✓					✳				✓	✓	✓				
M. Zhang and Pel (2016)		✓		✳			✓		✳			✳	✓	✓	✓	✳			
Y. Zhang et al. (2021)	✓	✓		✓					✓		✳	✓	✓	✓	✓				
Y. Zhang et al. (2022a)	✓	✓		✓					✓		✳	✓	✓	✓	✓	✳			
Y. Zhang et al. (2023)	✓	✓		✓	✓				✓		✳	✓	✓	✓	✓				
Zweers et al. (2020)	✓	✓		✓								✓	✓	✓	✓				
This research		✓	✓	✓		✓	✓	✓	✓				✓	✓	✓	✓	✳	✳	

Table 2.2 highlights several important points. At the bottom of the table, this research is also classified using the same categorisation. Among the papers focused on synchromodality, such as Tavasszy et al. (2017), M. Zhang and Pel (2016), and Van Riessen et al. (2015), primarily examine the concept of synchromodality itself. Other papers, including Pfoser et al. (2016), M. Zhang and Pel (2016), and Giusti et al. (2019), focus more on its potential and success factors. By contrast, this research is designed to focus more on the quantitative side of synchromodal transportation. Prior studies by Guo et al. (2020), Guo et al. (2022), Y. Zhang et al. (2021), Rivera and Mes (2022), Y. Zhang et al. (2022a), and Y. Zhang et al. (2023) have addressed the quantitative dimension, mainly focusing on the planning of transport requests in a synchromodal context. Building on these studies, this research contributes by explicitly modelling container terminals as active nodes that interact within the system, thereby advancing the existing literature.

The modelling of container terminal operations has been explored from various quantitative angles. For example, Murty et al. (2005), Rida et al. (2011), and Hamdy et al. (2022) focus on terminal decision-making while Fotuhi et al. (2013) focuses on yard crane optimisation, Zehendner and Feillet (2014) examines truck flows at inland terminals, and Hirashima (2016) emphasising rail operations in container yards. In contrast to these studies, and similar to the line of work by Hirashima et al. (2006), Lee et al. (2006), B. Jin and Tanaka (2023), Ng and Talley (2020), L. Wang and Zhu (2019), and Zweers et al. (2020), this research focuses specifically on container stacking problems. Additionally, works like Clemente et al. (2023), Filom et al. (2022), and Gharehgozli et al. (2019) explore long-term port development and capacity planning. While this research does not directly contribute to these broader strategic discussions, it investigates whether synchromodality introduces specific challenges or requirements that affect the future-proofing of terminals.

Other notable works address contextual or policy-related factors relevant to this research. For example, demurrage and detention of Fazi and Roodbergen (2018) and Storms et al. (2023). Likewise, environmental considerations such as carbon taxation and sustainability are explored by Memari et al. (2021), X. Wang et al. (2020), and Yuan et al. (2023), all of which relate indirectly to themes considered in this study.

In summary, the thematic overview of the literature highlights the gap between studies focused on synchromodality and those employing quantitative methods, as well as the gap between research on synchromodality and container terminal development. Although there are several quantitative studies for synchromodality, they have not been widely applied, mainly focusing on the mechanics required for transport planning but not in a much wider scope. This gap — a lack of quantitative studies focusing on synchromodality and container terminal operations — presents an opportunity for further research. By addressing this, the research contributes to more practical and data-driven insights into the operational benefits of synchromodality in real-world logistics networks.

2.4. Theoretical Framework

This section presents the theoretical foundations of the research, building upon existing concepts highlighted in the bibliographic network and thematic overview of literature. This framework will be referred back to throughout the remainder of the research as a means of structuring methodology and shaping development steps.

2.4.1. Synchromodality as a Planning Paradigm

Synchromodality is a core aspect of this research and has to be accounted for in all aspects of the rest of the research. That means that every model or development in this research has to be done keeping synchromodality in mind; it acts as a central paradigm. Synchromodality builds upon traditional intermodal transportation but introduces greater capabilities in terms of balancing costs and environmental concerns as well as having greater adaptability to changing conditions. The theoretical basis for this paradigm lies in the principles of real-time coordination and networked decision-making, supported by the broader framework of integrated transport planning. The definition and conceptual development of synchromodality have been extensively addressed in previous work (Tavasszy et al., 2017; Van Riessen et al., 2015), whose definition will be used to shape this research.

2.4.2. Quantitative Models for Synchromodal Planning

Quantitative studies have been executed extensively in the logistics-based research body. In terms of synchromodality these quantitative studies have primarily focused on the transport planning and optimisation side. By addressing challenges such as flexible mode choice and sustainability concerns, it Y. Zhang et al. (2022b) presented a multi-objective optimisation model to address this. In a later paper, Y. Zhang et al., 2022a presented a new study with a heuristic algorithm for synchromodal transport planning, this time incorporating flexible services in the hinterland of the Rotterdam port area. These research efforts will play a crucial role in this research for emulating the synchromodal nature in transport planning.

2.4.3. Container Terminals as Active Nodes

While existing transport planning and optimisation models often ignore container terminals by treating them as passive transshipment nodes in the network, this research adopts a different approach in which container terminals are explicitly represented as active nodes. That is, terminals are not only constrained by upstream decisions but also exert influence over transport execution through yard availability, handling capacity, and scheduling policies. Existing research on container terminal operations and stacking optimisation has shown that this is an area that has been extensively researched with various applications (Boschma et al., 2023).

2.4.4. Integration of Policy and Environmental Considerations

The search procedure and thematic overview of literature also discussed numerous other considerations for logistics that relate to the broader advancements in logistics. These will also be incorporated within the research where possible. Some of these considerations, like sustainability concerns or demurrage and detention fees, are already embedded into other studies where emission or delay penalties are modelled (Memari et al., 2021; X. Wang et al., 2020; Yuan et al., 2023).

2.5. Conclusion on Literature Review

The literature review began with a structured search and bibliometric analysis, which provided a preliminary indication of a research gap at the intersection between synchromodality, quantitative methods, and container terminal operations. A thematic review of relevant studies further revealed that while synchromodality has been conceptually developed, its integration into container terminal operations, particularly through quantitative modelling, remains limited. This research fills that gap by focusing on the operational feasibility and performance impacts of integrating synchromodal planning with container terminal operations. It aims to make a contribution to this evolving field by combining several perspectives:

- Synchromodality as a real-time, flexible freight allocation paradigm;
- Quantitative operations research methods for synchromodal transport planning;
- Container terminals as active, decision-making entities in freight networks;
- Contextual policy considerations that affect operational feasibility.

3 Research Methodology

The research methodology for this research is outlined in this chapter. The research methodology offers thorough descriptions of the research design, chosen models & adaptations, data sources & criteria, experimental setup & development process, and limitations & assumptions in sections 3.1 through 3.6.

3.1. Research Design

The reseach is designed using synchromodality as a central planning paradigm as introduced in Chapter 2. This further considers contextual policy elements, active modelling of terminal decision-making processes and exising quantitative operations research. The eventual goal of the reseach is to answer the following research question:

”How does the integration of synchromodal transport planning and container terminal operations impact the efficiency of terminal operations, the adaptability of transport planning, and the overall cost-effectiveness of supply chain operations?”

The primary research question is broken down into three sub-research questions to help the research, each one is answered using a mix of literature review and simulation-based testing. Table 3.1 outlines the questions and associated methods. The research design provides the overall framework for answering the research questions by combining simulation experiments, literature insights, and scenario analysis. The remainder of this section provides a short description of the selected models and explains how they complement and reinforce one another within the research framework. The in-depth selection of methods and model adaptations is discussed in Section 3.2.

Table 3.1: Sub-research questions.

	Sub-research question
SQ.1	What are the key characteristics of synchromodality, and how do its complexities shape the integration of transport planning and container terminal operations?
SQ.2	How can interactions between transport planners and terminal operators be modelled to simulate decision-making, coordination, and real-time adaptability in synchromodal transport?
SQ.3	What real-world scenarios can be used to evaluate how the integration of synchromodal transport planning and container terminal operations impacts terminal efficiency, transport adaptability, and supply chain cost-effectiveness?

Given that this study employs synchromodality as a transportation planning framework, it is essential to specify how this idea is depicted. It is equally important to clarify how this system can be orchestrated, since synchromodal transport involves multiple stakeholders, such as freight forwarders, logistics service providers (LSPs), and terminal operators, each with individual objectives and decision-making processes. This orchestration is important, first of all, from a purely conceptual synchromodal perspective. Ensuring that there is a good understanding of how the synchromodal planning paradigm is used among these various stakeholders, which is further elaborated in Section 3.2.1.

A Multi-Agent System (MAS) is a technique that allows accurate modelling of such stakeholders, called agents, with particular goals as well as their dynamic interactions.parencitewooldridge-2009. The dynamic interactions in this study mostly characterise the mechanism whereby certain agents may affect other agents. As an example, assume a shipment has to wait for its service to start at a terminal agent, due to another shipment being serviced at that time. This might cause a delay which in turn affects the schedule of the planning agent, but also the operations of other terminal agents. The dynamic interactions would allow these agents to communicate such information so that they can adapt. These dynamic interactions are essential for examining how agents coordinate transport planning, container stacking, and repositioning under varying demand, network configurations, and terminal conditions. Section 3.2.4 discusses the technical and design aspects of setting up a MAS for this purpose.

In the proposed synchromodal Multi-Agent System, this research utilises operations research methods to perform transport planning. The Synchromodal Transport Planning Problem with Flexible Services (STPP-FS) by Y. Zhang et al., 2022a is utilised to represent this purpose, and will be placed in the MAS as the planning agent. The STPP-FS model traditionally plans shipments over links between nodes, where each node represents a decision point in the transport network, Section 3.2.2 goes into more detail about this model. In contrast to the work of Y. Zhang et al. (2022a), in this paper, the nodes are redefined as container terminals. This implies that rather than containers travelling from, through, or to a node, they now have to be recovered, moved, or placed within a terminal before their journey continues. Though it increases complexity, this change guarantees a more realistic depiction of logistical operations, as terminal designs and demand changes constantly affect service delays. The MAS has to let the STPP-FS, as the planning agent, communicate with these active decision-making units to exchange information on these dynamic service times.

Having container terminals as active, decision-making entities in freight networks is a very interesting and important aspect of this research, so that it explicitly models dynamic terminal operations and capacity constraints. This can help to test a key advantage of synchromodal transport that is its ability to adapt to disruptions by dynamically switching transport modalities. For example, during periods of low water levels in the Rhine or Maas rivers, synchromodal transport allows containers to be rerouted through alternative modes. However, this flexibility is constrained by the finite operational capacity of terminals, which can become saturated if too many shipments are rerouted through a single hub. If the modelling of terminal operations is not taken into account, this can lead to unrealistic replanning of the transport plan, where all shipments are rerouted through the same node without saturation. Terminal operations will be modelled using the Stacking Problem (SP) definition by Expósito-Izquierdo et al. (2015), which provides a structured approach to container retrieval, repositioning, and placement within terminals. Section 3.2.3 explains why this model was chosen and what other models and considerations were taken.

The STPP-FS and SP models will be integrated within a Multi-Agent System to reflect realistic logistics operations. In this system:

- Freight forwarders and logistics service providers (LSPs), represented by the STPP-FS model, are responsible for transportation planning and routing decisions.
- Container terminals, represented by the SP model, manage stacking operations, retrieval, and placement while responding to changing transport demands.
- Agent-based communication ensures coordination between these stakeholders, allowing dynamic transport planning and decision making.

By combining simulation, Multi-Agent System modelling, and optimisation, this research can evaluate how synchromodality affects resilience and efficiency in inland container terminals. The simulation framework offers insight into the viability of synchromodal techniques in actual logistics networks by means of controlled tests under different demand scenarios and disturbance situations. The next parts offer a thorough summary of the chosen models and a justification for their selection over other options.

3.2. Selected Methods

This section presents the selected methods and highlights the key adaptations necessary to apply them within the context of synchromodality and inland container terminal operations. It explains the methodological foundations of the study, describes how these methods were tailored to fit the specific research context, and provides a rationale for their selection. This framing helps to clarify how the methods address the research questions and operational challenges outlined in the earlier chapters.

3.2.1. Synchromodality as a Planning Paradigm

Synchromodality represents an innovative approach to freight transport that enhances efficiency, sustainability, and flexibility through dynamic multimodal integration. Emerging as a prominent concept in the Benelux region over the past decade, synchromodal transport leverages advanced information systems and intelligent transportation technologies to optimise logistics operations. By coordinating transport flows and synchronising multimodal transport networks, synchromodality facilitates seamless transitions between different transport modes, ensuring that freight movements align with real-time demands and operational constraints (Giusti et al., 2019; Tavasszy et al., 2017).

At its core, synchromodal transport planning promotes collaboration among key stakeholders, including shipping companies, inland container terminals, transport authorities, and government bodies. This integrated approach enables stakeholders to make data-driven decisions, dynamically allocate resources, and enhance the resilience of transport networks. Unlike traditional intermodal transport, which focuses more on vertical integration of logistics services within a single transport chain, synchromodality emphasises horizontal integration throughout the transport system (Giusti et al., 2019). Figure 3.1 depicts the interrelationship of supply chain stakeholders with a potential role in synchromodal logistics, including different types of LSPs.

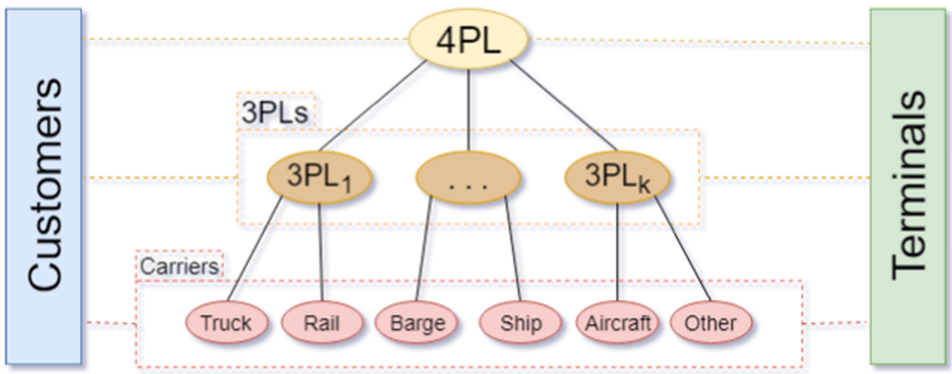


Figure 3.1: Logistics stakeholders and their interrelationships.

Note. Reprinted from (Giusti et al., 2019).

Pfoser et al. (2016) delves into defining the characteristics and critical success factors (CSFs) of synchromodality for its stakeholders, later Giusti et al. (2019) reviews these identified CSFs and matches them with enabling technologies (Figure 3.2). Giusti et al. (2019) further underscores the importance of technological synergies and calls for the development of a common platform to synchronise the operations of stakeholders. Such a platform would streamline business processes and foster cooperation. The authors propose the introduction of a 5PL (Fifth-party logistics) service provider as a "synchromodality orchestrator," coordinating activities across the supply chain (Figure 3.3). This new type of service provider could integrate operations not just for transportation but for all supply chain activities, maximising collaboration across one or more supply chains. This 5PL structure gives an outline of how a MAS could be structured and how the agents within the MAS should operate to keep a realistic synchromodal nature.

Enabling technologies	Critical success factors: Network, collaboration and trust	Sophisticated planning	Physical infrastructure	Legal and political framework	Awareness and mental shift	Pricing, cost, service
Traceability	✓			✓		
Intelligent systems		✓	✓			
Data analytics		✓			✓	✓
Optimization		✓	✓			✓
Simulation	✓	✓	✓		✓	
Integration platforms	✓			✓	✓	✓

Figure 3.2: Critical success factors and enabling technologies.

Note. Reprinted from (Giusti et al., 2019).

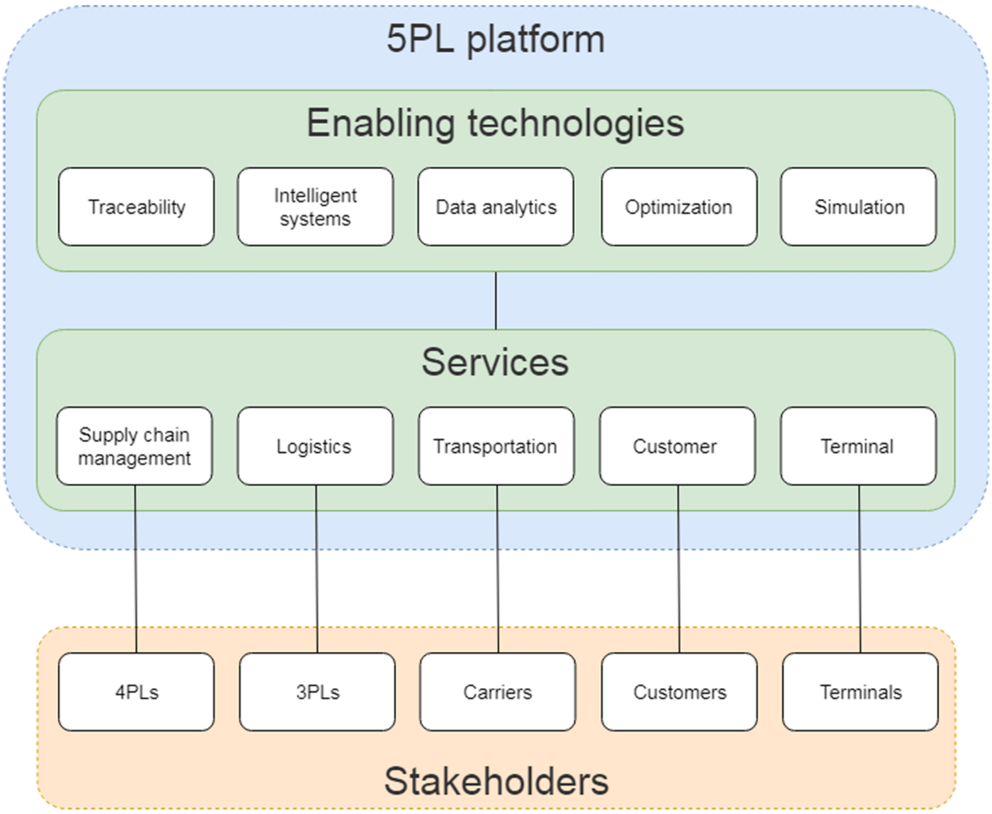


Figure 3.3: Fifth-Party Logistics (5PL) platform.

Note. Reprinted from (Giusti et al., 2019).

Characteristics of Synchromodality

There is no universally agreed definition of synchromodality, therefore it is interesting to subdivide the concept of synchromodality into key characteristics. These key characteristics can later be used to check and ensure that an environment is synchromodal. For this research six characteristics are defined and shown in Table 3.2 with a short definition. These characteristics have been cross-referenced with numerous papers to ensure their relevance in Table 3.3.

Table 3.2: Characteristics of synchromodality.

Characteristic	Description
Flexible Mode Selection	Amodal booking allows customers to leave transport mode decisions to LSPs, enabling adaptive mode shifts based on real-time conditions. Ensures efficient handling of disruptions by dynamically switching between available transport modes.
Real-time Data Exchange	Stakeholders require continuous data flow to optimise routing, scheduling, and resource allocation. Examples include railway traffic rescheduling and adaptive vessel routing based on port congestion and weather conditions.
Cost and Time Optimisation	Optimising transport choices based on real-time conditions reduces costs and improves delivery times. Smart steaming, for instance, optimises transit time to minimise idle waiting at ports — not necessarily choosing the fastest route, but the most efficient use of time.
Environmental Sustainability	Prioritising sustainable modes (e.g., rail, barge) over trucks helps minimise emissions. Practices like slow steaming and smart steaming further enhance energy efficiency in transport.
Collaboration Across Stakeholders	Encourages both vertical (supply chain integration) and horizontal (cooperation between similar service providers) collaboration. Shared infrastructure, joint planning, and real-time data exchange improve network resilience.
(Physical) Infrastructure Adaptions	Investments in intermodal hubs, digital platforms, and coordination systems ensure smooth transitions between transport modes.

Note. Derived from (Giusti et al., 2019).

Table 3.3: Referenced characteristics of synchromodality.

	Flexible mode selection	**Real-time data exchange**	**Cost and time optimisation**	**Environmental sustainablity**	**Collaboration across stakeholders**	**Infrastructure adaptation**
Giusti et al. (2019)	✓	✓	✓	✓	✓	✓
Pfoser et al. (2016)	✓	✓	✓	✓	✓	✓
Van Riessen et al. (2015)	✓	✓	✓	✓	✓	✳
Tavasszy et al. (2017)	✓	✓	✓	✓	✓	✓

Note. ✓: Characteristic directly referenced.; ✳: Van Riessen et al., 2015 does not explicitly reference changes to the physical infrastructure, but does reference technical infrastructure.

Table 3.4 shows the key characteristics of synchromodality and if it affects or should be modelled within the STPP-FS, SP, or MAS. Flexible Mode Selection, Cost and Time Optimisation, and Environmental Sustainability are primarily linked to the planning dimension of synchromodal transport. These factors guide transport decision-making and are embedded in the STPP-FS model. Real-Time Data Exchange and Collaboration Across Stakeholders are critical on both the planning and terminal operations sides and must be supported by the MAS framework. Finally, Infrastructure Adaptation is addressed within the SP model for physical operations and the MAS for enabling technical coordination.

Table 3.4: Key characteristics of synchromodality and their impacts.

Characteristic	STPP	SP	MAS
Flexible mode selection	✓		
Real-time data exchange	✓	✓	✓
Cost and time optimisation	✓		
Environmental sustainability	✓		
Collaboration across stakeholders	✓	✓	✓
Infrastructure adaptation		✓	✓

Note. Derived from (Giusti et al., 2019).

3.2.2. Synchromodal Transport Planning

Synchromodal transport planning or scheduling is an optimisation method aiming to model the synchromodal decision-making process, considering the benefits of synchromodal freight transport in terms of cost reduction, reliability, and sustainability. A few articles have discussed this, Guo et al. (2020) focused on a platform that provides online matches between shipment requests from shippers and transport services from carriers, using a heuristic algorithm and a rolling horizon approach. In a later paper, Guo et al. (2022) presented an extended shipment matching problem, implementing a reinforcement learning approach. Similarly, Rivera and Mes (2022) introduced an anticipatory synchromodal shipment scheduling approach using a Markov Decision Process (MDP) and proposed a heuristic solution based on Approximate Dynamic Programming.

Y. Zhang et al. (2021) presented a multi-objective optimisation model to address the different objectives of carriers in synchromodal transport. In a later paper, Y. Zhang et al. (2022a) proposed a new model with a heuristic algorithm for synchromodal transport planning, this time incorporating flexible services, in the hinterland of the Rotterdam port area (Figure 3.4). Rather than just determining which shipments should be transported using available services, this model also considered making changes to routing plans for barges and trucks based on shipment demand. This study specifically focuses on the scheduling aspect, with container terminals simplified as nodes where containers transfer between modes. While the studies account for time or cost penalties associated with container handling, they do not model the operations of the terminals themselves. To summarise the characteristics of the proposed STPP-FS include multiple modes of transports, transshipment opportunities, the mix of fixed and flexible vehicle services, complex schedules consisting of waiting, storage, and delay times, and synchronisation to coordinate vehicle schedules.

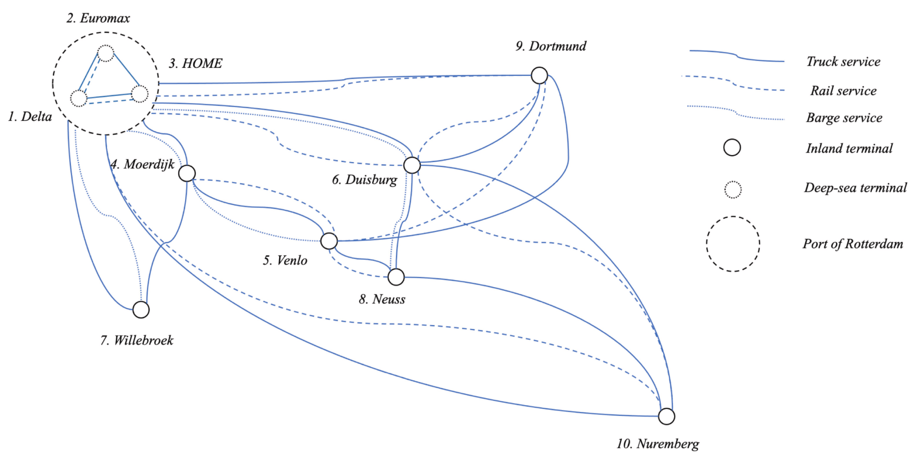


Figure 3.4: Transport network based on European Gateway Services (EGS).

Note. Reprinted from Y. Zhang et al. (2022b).

Adaptive Large Neighbourhood Search
Due to the computational complexity of the mathematical model of the STPP-FS, Y. Zhang et al. (2022a) proposed an Adaptive Large Neighbourhood Search (ALNS) heuristic to solve the problem. The ALNS heuristic is designed to efficiently solve the synchromodal transport planning problem with flexible services. The solution process consists of three main components: the construction of an initial solution, the application of removal and insertion operators, and the feasibility check including synchronisation constraints. The ALNS heuristic employs a set of operators that iteratively modify the solution to improve feasibility and reduce costs. These operators are categorised into insertion, removal, and swap mechanisms, as presented in Table 3.5.

Table 3.5: Adaptive Large Neighbourhood Search operators.

Characteristic	Description
Greedy insertion	Inserts requests in the most cost-effective position.
Regret insertion	Prioritises insertions based on regret values to avoid future infeasibilities.
Transshipment insertion	Ensures efficient placement of requests requiring transshipment.
Worst removal	Eliminates the most costly requests.
Random removal	Removes requests randomly to enhance exploration of the solution space.
Related removal	Removes clusters of similar requests for more efficient repositioning.
Swap operator	Combines history removal and greedy insertion to improve request placement.

Note. Derived from Y. Zhang et al. (2022a).

Dynamic Synchromodal Transport Replanning
Transportation planning is frequently challenged by various uncertainties that can considerably affect transport efficiency. One of those uncertainties is service time uncertainty, service time in synchromodal transport refers to the duration of picking up, delivering, or transferring goods at terminals, including all loading or unloading activities and related processes. Although the goal of synchromodal transport is to ensure seamless and efficient goods transfer between modes, the inherent uncertainties at terminals, caused by congestion, inclement weather, equipment malfunctions, and other unanticipated events, can lead to extended waiting times and rendering transport plans infeasible. Consequently, low efficiency, high costs, and even cancellations of requests can occur.

A critical component of synchromodal freight transport, is the ability to adapt to such service time uncertainties at terminals. To address transport planning problems in the presence of these uncertainties, Y. Zhang et al. (2022a) proposes a dynamic replanning algorithm (Algorithm 1), aiming to mitigate the negative effects of service time variability and enhance the robustness and reliability of synchromodal operations for future work. This dynamic replanning algorithm will serve as the basis for the to be developed scenario analysis module in the MAS.

In conclusion, the STPP-FS is a fundamental model for this research which is largely adopted without substantial modifications or refinements. According to the Table 3.4 the key characteristics of synchromodality that strictly need to be represented in the STPP-FS are flexible mode selection, cost and time optimisation, and environmental sustainability. The flexible mode selection, cost and time optimisation, and environmental sustainability characteristics are all included in the STPP-FS. Cost and time optimisation and environmental sustainability are both included in the objective of the STPP. Represented by transportation costs, time windows and carbon taxation. Flexible mode selection is inherently part of the STPP-FS since the planner has all authority to decide which modes are used for what kind of request. In addition to that Y. Zhang et al. (2022a) proposed a dynamic replanning algorithm which will be further explored in Chapter 4. The STPP-FS serves as the core planning module within the MAS framework of this research. Its alignment with key synchromodal characteristics makes it suitable for evaluating flexible routing decisions, sustainability objectives, and operational resilience.

Algorithm 1 Dynamic replanning algorithm.
Note. Reprinted from (Y. Zhang et al., 2022a).

Input: K, R, N, A **Output:** X_{best}
Set X_{current} as empty routes of K;
$X_{\text{best}} = ALNS(K, R, N, A, X_{\text{current}})$
for time in time_horizon **do**
  $X_{\text{current}} \leftarrow X_{\text{best}}$
  if new information of requests is revealed **then**
    Define the set of changed requests as R_{change}
    Remove unfinished parts of changed $r \in R_{\text{change}}$ from X_{current}, and set this new current solution as X'_{current}
    $X_{\text{best}} = ALNS(K, R_{\text{change}}, N, A, X'_{\text{current}})$
return X_{best}

3.2.3. Container Stacking Optimisation

During transport, intermodal containers are often stored at terminals, where they are typically stacked to optimise space use. However, this stacking can lead to unproductive relocation moves when a container located beneath another needs to be retrieved. Minimising these relocations offers financial advantages by reducing the direct costs associated with relocation operations and reducing the time required to access the desired container. Boschma et al. (2023) proposed a dynamic programming approach for container stacking.

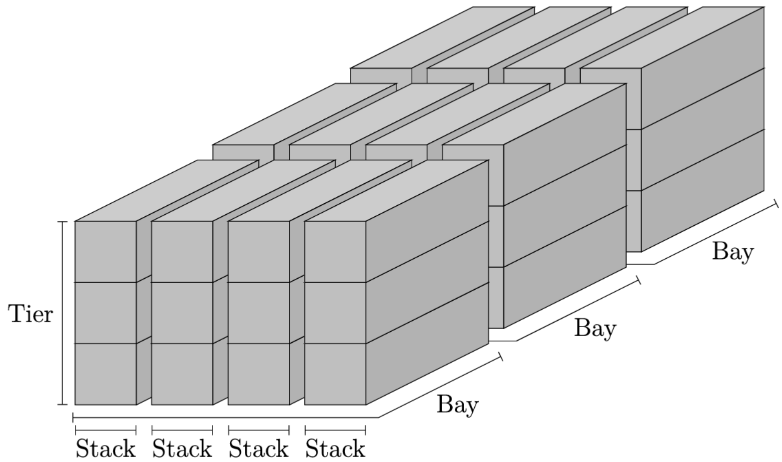


Figure 3.5: Visualisation of the bay, stack, and tier structure.

Note. Reprinted from (Boschma et al., 2023).

Container stacking optimisation is a well-explored area, under multiple names like the Container Relocation Problem (CRP) and the Block Relocation Problem (BRP). For the purpose of this research it is important to select the right container stacking optimisation that can facilitate the synchromodal nature. As described in Boschma et al. (2023), numerous considerations must be taken into account before a model can be defined. Examples include the types of stacks and equipment used in a container yard. Depending on the equipment, different types of restrictions should be in place. For example, a crane can move over a stack and place or retrieve containers from the middle of a bay, while a reachstacker can only approach a stack from the side, which means it can only handle containers at the edge of the stack, as illustrated in Figure 3.5. Other considerations identified for container stacking optimisation are listed in Table 3.6.

Table 3.6: Container stacking optimisation considerations.

Consideration	Description
Type of Problem	• Handling of inbound containers • Handling of outbound containers • Handling of both inbound and outbound containers
Shipment arrival and departure order	• Containers arrive and depart in a single known sequence • Containers arrive and depart in a single unknown sequence • Containers arrive and depart in batches, with the order of the batches known but the order of containers within each batch unknown • Containers arrive and depart in batches, with both the order of the batches and the order of containers within each batch unknown
Optimisation goal(s)	• Minimising the number of relocations • Reducing transportation costs • Minimising the number of adjacent unordered stacks
Optimisation method	• Genetic Algorithm • (Binary) Integer Programming • Heuristic approaches • Branch and Bound • Decision Trees • (Stochastic/Approximate) Dynamic Programming

Note. Derived from (Boschma et al., 2023).

Given that the terminal agent will have to interact with the synchromodal transport planning agent, the following decisions can be made. Considering the type of problem, it will need to handle both inbound and outbound containers. For shipment arrivals and departures, it can be assumed that they will arrive and depart in batches where the order of the containers is unknown. The nature of synchromodality might cause the content of the batches i.e. the combination of containers to alter over time based on the synchromodal planning. The order of the batches themselves is dependent on numerous assumptions, specifically the flexible services next to fixed services will cause the order of batches to be subject to change.

With respect to optimisation goals, minimising costs would be an interesting target, as this monetary value could be useful in negotiations with the synchromodal transport planning agent. This objective is correlated with minimising the number of relocations, which could also be a goal. However, it is important to note that minimising the number of relocations does not differentiate between small and large relocations; for example, moving a container within a stack versus moving a container between stacks at the opposite side of the yard. An important note is that these are the optimisation goals specifically for the container stacking. The goal of a container terminal would be more focused on maximising throughput and maximising profit. Finally, Boschma et al. (2023) argues convincingly for solving this type of problem heuristically (using methods such as Approximate Dynamic Programming), as it is often infeasible to solve such problems exactly with modern computers.

Overview of Container Stacking Models

This paragraph provides an overview of various models for container stacking in terminal operations, highlighting specific papers and addressing aspects such as objectives, movement restrictions, and container handling processes. Table 3.7 summarises the different problem types along with notable papers that have been studied.

Table 3.7: Detailed overview of container stacking models by paper.

Problem type	Paper (Author/Year)	Moves (Restricted / Unrestricted)	Container handling (Inbound / Outbound)
PSLP	Boysen and Emde (2016)	Unrestricted	Inbound only
	Boge and Knust (2019)	Restricted and Unrestricted	Inbound only
BRP / CRP	Kim and Hong (2004)	Restricted	Inbound only
	Caserta et al. (2009)	Restricted	Inbound only
	Caserta et al. (2011)	Restricted	Inbound only
	Zehendner et al. (2015)	Restricted	Inbound only
	Zehendner et al. (2016)	Restricted	Both inbound and outbound
	De Melo Da Silva et al. (2018)	Restricted and Unrestricted	Inbound only
	B. Jin and Tanaka (2023)	Restricted and Unrestricted	Inbound only
DCRP	Akyüz and Lee (2014)	Restricted and Unrestricted	Both inbound and outbound
	Akyüz (2017)	Restricted and Unrestricted	Both inbound and outbound
SP	Expósito-Izquierdo et al. (2015)	Restricted and Unrestricted (Event-based or Non-event-based approaches)	Both inbound and outbound

Note. PSLP: Parallel Stack Loading Problem; BRP: Block Relocation Problem; CRP: Container Relocation Problem; DCRP: Dynamic Container Relocation Problem; SP: Stacking Problem

Parallel Stack Loading Problem (PSLP)
Primary Papers: Boysen and Emde (2016) & Boge and Knust (2019). The PSLP aims to optimise loading containers into parallel stacks to minimise the number of relocations during stacking. This model assumes a structured stack arrangement and focuses on improving efficiency by organising containers based on retrieval order. The PSLP generally permits unrestricted moves within parallel stacks to minimise relocations and primarily focuses on outgoing containers.

Block Relocation Problem (BRP)
Primary Paper: Kim and Hong (2004). The BRP addresses the reorganisation of containers in a single block (container) to improve access to specific containers buried deep in the stack. The objective is to minimise relocation moves needed to retrieve these containers. Only restricted moves (moving only top containers) are allowed, focusing solely on outgoing containers.

Container Relocation Problem (CRP)
Primary Papers: Caserta et al. (2009) & Caserta et al. (2011). The CRP minimises retrieval costs by organising stacks through relocations, which can be done only under restricted moves, where only top containers are moved to unblock lower ones. This problem primarily considers outgoing containers in the stacking and retrieval process.

Dynamic Container Relocation Problem (DCRP)
Primary Paper: Akyüz and Lee (2014). The DCRP extends the CRP by incorporating dynamic elements, such as simultaneous handling of incoming and outgoing containers. This model seeks to minimise relocation moves while adjusting for container arrivals and departures. It includes both restricted and unrestricted moves, depending on operational needs, and considers both incoming and

outgoing containers continuously.

Stacking Problem
Primary Paper: Expósito-Izquierdo et al. (2015). The Stacking Problem aims to minimise the number of container relocations. This paper presents a heuristic that includes an algorithm to optimise idle time between shipments. It incorporates event-based and non-event-based approaches and continuously considers both incoming and outgoing containers. The SP model by Expósito-Izquierdo et al., 2015 is one of the few that handles both inbound and outbound flows while allowing event-based and idle-time operations.

Table 3.4 identified that the selected SP should contribute to the real-time data exchange and collaboration across stakeholders characteristics to ensure that the synchromodal nature is preserved. Since none of the discussed stacking models natively support these features, they will be developed in Chapter 4. Following the overview from Boschma et al. (2023), there needs to be a defined type of problem, shipment arrival and departure order, optimisation goal, and optimisation method when selecting the stacking model. Based on the characteristics of synchromodal transport it can be concluded that the model should possess the following characteristics as identified in Table 3.8.

Table 3.8: Selected container stacking model considerations.

Consideration	Description
Type of Problem	• Handling of inbound containers • Handling of outbound containers • **Handling of both inbound and outbound containers**
Shipment arrival and departure order	• Containers arrive and depart in a single known sequence • Containers arrive and depart in a single unknown sequence • Containers arrive and depart in batches, with the order of the batches known but the order of containers within each batch unknown • **Containers arrive and depart in batches, with both the order of the batches and the order of containers within each batch unknown**
Optimisation goal(s)	• **Minimising the number of relocations** • Reducing transportation costs • **Minimising the number of adjacent unordered stacks**
Optimisation method	• Genetic Algorithm • (Binary) Integer Programming • **Heuristic approaches** • Branch and Bound • Decision Trees • (Stochastic/Approximate) Dynamic Programming

Note. Derived from (Boschma et al., 2023).

The model should be able to handle both inbound and outbound containers, the order in which batches arrive is unknown (or at least subject to last-minute changes) and the order in which containers are loaded and unloaded is unknown, the optimisation goal would minimise the number of relocations or minimise the number of unordered stacks and for the optimisation model a heuristic approach is preferred since container stacking is often identified as NP-hard especially when models consider unrestricted moves.

Given these characteristics, the model proposed by Expósito-Izquierdo et al. (2015) is chosen for this research primarily due to its alignment with the requirements. As this model is designed to exploit idle time in its operations, it provides a non-event-based approach that enhances performance by utilising idle periods for strategic container rearrangement. This feature is particularly beneficial in reducing the number of adjacent unordered stacks and maintaining efficient operations within the time-constrained nature of the STPP.

This model, like others, does however have a few limitations that have to be addressed. This model only considered a single storage area (bays x stacks x tiers), in reality, terminals can have unique features with dedicated storage areas. For example a dedicated storage near the quay for barge operations and another storage yard near the tracks for rail operations. Placing a container near the quayside while it is supposed to leave by train could impose extra operations in the limited space that is available near the quayside and vice versa. Additionally, terminals can have dedicated storage areas for different types of containers such as reefer containers or empty containers. Which immediately points out another limitation and that is that there are no container characteristics. Chapter 4 will dive into how these limitations are resolved. The remainder of this section focuses on the detailed explanation of the SP.

Stacking Problem

The Stacking Problem is based upon the mathematical modal proposed by Rei and Pedroso (2011). The heuristic algorithm is designed to store and retrieve a set of containers in storage within a certain timeframe, to minimise the number of relocations. For this purpose, the following sets, parameters and variables are defined in Table 3.9. Note that the variables in this heuristic consist of variables of this SP that get updated after each iteration of the algorithm. Further Expósito-Izquierdo et al. (2015) refers to containers as 'blocks', an incorrectly placed container is referred to as a 'non-located block' and a correctly placed container is referred to as a 'well-located block'. For the remainder of this section, the term block is replaced by container to avoid confusion.

To illustrate how the SP works it is important to start off by assessing what sets, parameters and variables are used from Table 3.9. Figure 3.6 can be used to explain this in detail. This figure shows eight stacks, $S = \{1, 2, ..., 8\}$, and five tiers, $T = \{1, 2, ..., 5\}$, resulting in a storage with a capacity of $M = 20$. The incoming containers are on the left, the current storage configuration is in the centre, and the outgoing containers are on the right. The number indicating each container corresponds with the retrieval time for that container (r_c). Specifically for the incoming containers ,there is a dedicated number below the container indicating its arrival or delivery time (d_c) (Expósito-Izquierdo et al., 2015).

For the container-based variables s_c and t_c indicate the location for each container, so for the container with $r_c = 79$, $s_c = 1$, and $t_c = 1$. The set of containers above this container is $O_c = \{43, 45\}$. For the stack-based variables, h_s indicates the height so $h_1 = 3$ and $h_2 = 4$, with min_s indicating the earliest retrieval time for a container in that stack so $min_1 = 43$ and $min_2 = 37$. For the container placement Φ is used to identify the stacks that have available space so $\Phi = S4$, while Ω_s indicates the incorrectly placed containers and γ_s indicates the correctly placed containers in each stack. For the third stack $\omega_3 = \{54, 67\}$ and $\gamma_3 = \emptyset$, and for the fourth set $\omega_4 = \{26, 83\}$ and $\gamma_4 = \{39, 68, 87\}$. Finally, Ω is the set for all incorrectly placed containers, which in this case is the set of all gray containers from Figure 3.6 (Expósito-Izquierdo et al., 2015).

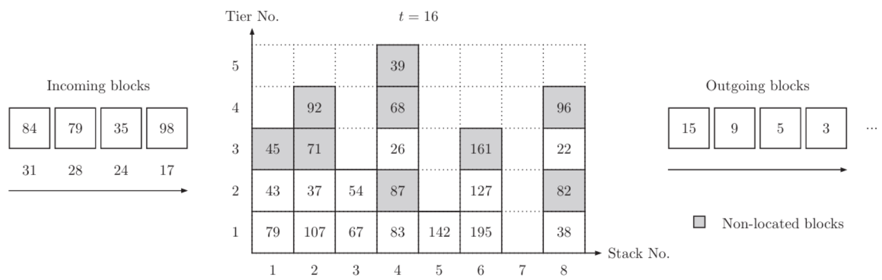


Figure 3.6: Example of stacking problem with $nS = 8$ stacks and $nT = 5$ tiers.

Note. Reprinted from (Expósito-Izquierdo et al., 2015).

Table 3.9: Stacking Problem sets, parameters, and variables.

Sets and indices		
C	Set of homogeneous containers	$C = \{1, 2, \ldots, nC\}$
S	Set stacks	$S = \{1, 2, \ldots, nS\}$
T	Set tiers	$T = \{1, 2, \ldots, nT\}$
Parameters		
H	Horizon of timeframe to model	[timestep]
M	Capacity of storage defined as $M = nS \cdot nT$	[containers]
d_c	Delivery time for container c	[timestep]
r_c	Retrieval time for container c	[timestep]
Variables & Functions		
s_c	Current stack for container c	$s_c \in S$
t_c	Current tier for container c	$t_c \in T$
O_c	Set of containers above given container c	$O_c = \{c' \in C \mid (s_{c'} = s_c) \wedge (t_{c'} > t_c)\}$
h_s	Number of containers in stack s	$h_s = \max\{t_c \mid (c \in C) \wedge (s_c = s)\}$
min_s	Earliest retrieval time of a container in stack s	$min_s = \min\{r_c \mid (c \in C) \wedge (s_c = s)\}$
Ω_s	Set of non-located containers in stack s	$\Omega(s) = \{c \in C \mid (s(c) = s) \wedge \exists c' :$ $(s(c') = s) \wedge (t(c') < t(c)) \wedge (r(c') < r(c))\}$
γ_s	Set of well-located containers in stack s	$\gamma_s = \{c \in C \mid (s_c = s) \wedge (c \notin \Omega_s)\}$
Ω	Set of non-located containers	$\Omega = \bigcup_{s \in S} \Omega(s)$
Φ	Set of stacks in which a container can be placed	$\Phi = \{s \in S \mid h_s < nT\}$

Note. Reprinted from (Expósito-Izquierdo et al., 2015).

SP Heuristic Algorithm

The heuristic is based on three different types of movements that can happen within a storage area, these being a delivery (inbound) movement where an incoming container is stored at the top of one of the stacks in Φ, a retrieval (outbound) movement when an outgoing container is removed from the top of a stack, and finally, a relocation movement when a container in Ω is relocated. The heuristic uses two algorithms, the first one dedicated to solving the SP (Algorithm 2), and the second one dedicated to improving the storage configuration during idle time. The general rationale of the algorithms is that for a container that needs to be stored or relocated, it will be moved towards the most attractive stack available and if a container is blocking another container it should be removed (Expósito-Izquierdo et al., 2015).

Going over Algorithm 2 the logic is as follows. For each time between the start time and the end time H two sets are defined, being the set of containers to release (inbound) in time t or the set of containers to retrieve at time t. If there are any outbound containers, it will check for each one of those containers if containers are blocking them, $O_c \neq \emptyset \forall s \in R_c(t)$, if that is the case each container in O_c will be moved out of the way to a new stack according to Equation 3.1 before the target container is eventually retrieved. If there are containers delivered to the stack the most attractive stack for that container will be selected according to Equation 3.1 and then it will be placed there. In case there are no deliveries or retrievals then it will move on to the improvement algorithm until there are incoming or outgoing containers (Expósito-Izquierdo et al., 2015).

$$f(c,s) = \begin{cases} \infty, & h(s) = nT \\ K, & h(s) = 0 \\ \min(s) + \frac{h(s)}{nT}, & 0 < h(s) < nT \wedge \min(s) \geq r(c) \\ 2K - \min(s) + \frac{h(s)}{nT}, & 0 < h(s) < nT \wedge \min(s) < r(c) \end{cases} \tag{3.1}$$

Algorithm 2 Stacking Problem solver algorithm.
Note. Reprinted from (Expósito-Izquierdo et al., 2015).

for $t = 0 \rightarrow H - 1$ **do**
  $D_C(t) \leftarrow$ Set of containers to release in time t
  $R_C(t) \leftarrow$ Set of containers to retrieve in time t
  if $R_C(t) \neq \emptyset$ **then**
    for $c \in R_C(t)$ **do**
      for $c' \in O(c)$ **do**
        $s \leftarrow$ Select target stack for c' according to Eq. (3.1)
        Relocate c' in s
      Retrieve c from the top of its stack
  if $D_C(t) \neq \emptyset$ **then**
    for $c \in D_C(t)$ **do**
      $s \leftarrow$ Select target stack for c according to Eq. (3.1)
      Place c in s
  if $D_C(t) \cup R_C(t) = \emptyset$ **then**
    Reduce the number of non-located containers by using the improvement strategy

The calculation of the attractiveness is shown in Equation 3.1, to calculate the attractiveness of stack s for container c. It consists of four rows, with the most attractive stacking receiving the lowest score. The first row states that if a stack is full the attractiveness is ∞ since it cannot store any more containers. If a stack is empty it is set to K with $K = 1 + \max\{r_c \mid c \in C\}$. If stack s is not empty and min_s of that stack is greater than or equal to r_c for container c, it means that a container can be placed in that stack an be well-placed. In that case, the attractiveness is set to $min(s) + \frac{h_s}{nT}$. Otherwise when a container is badly placed the attractiveness will be $2K - min(s) + \frac{h_s}{nT}$ (Expósito-Izquierdo et al., 2015).

There are a few interesting characteristics of this attractiveness function. Since the value of K is set to be one unit of attractiveness higher than the latest retrieval time. This attractiveness function will always prefer putting a container on top of another container if that does not cause an incorrectly placed container, so $min(s) + \frac{h_s}{nT} < K$, assuming $h_s < nT$. On the other hand, the attractiveness of placing a stack which would be an incorrectly placed container will always be greater than placing it in an empty stack. The term min_s for the third row ensures that the stack with its min_s closest to r_c for container c is selected, which causes containers with similar retrieval times to be placed together. The same term in the fourth row causes the model to prefer the opposite, preferring stacks with a high min_s. This maximises the time and thus chance to relocate the incorrectly placed container before the container below needs to be retrieved. Lastly the term $\frac{h_s}{nT}$ in rows three and four acts as a tiebreaker in case the base attractiveness of two stacks is the same the stack with the highest number of containers will be preferred (Expósito-Izquierdo et al., 2015).

Finally, Algorithm 3 shows the pseudo code for the improvement strategy that is applied during idle time between inbound and outbound containers. What this algorithm does is check if there are incorrectly placed containers to relocate, $Omega \neq \emptyset$, and if there are correctly placed stacks to locate them to, $Chi \neq \emptyset$. If this is the case for each incorrectly placed container it will be checked if it can be placed into a stack that is correctly stacked. Meaning that container c is currently at the top of its stack so that it can be picked up by a crane and $r_c \leq min_s$ so that it does not cause an incorrectly placed container in the other stack. This algorithm will run until there are no more feasible improvements to be made or until there are inbound or outbound containers (Expósito-Izquierdo et al., 2015).

Algorithm 3 Stacking Problem improvement strategy.
Note. Reprinted from (Expósito-Izquierdo et al., 2015).

Require: t_{min}, earliest time period to use
Require: t_{max}, latest time period to use
  for $t = t_{\text{min}} \rightarrow t_{\text{max}}$ **do**
    if $\chi \neq \emptyset \wedge \Omega \neq \emptyset$ **then**
      $placed \leftarrow$ **false**
      while $\neg placed$ **do**
        $c \leftarrow$ Select non-located container from Ω
        $s \leftarrow$ Select target stack from χ for c
        if $\exists c \wedge \exists s$ **then**
          if c can be moved toward s **then**
            Relocate c in s
            $placed \leftarrow$ **true**
        else
          $placed \leftarrow$ **true**

3.2.4. Multi-Agent System

A Multi-Agent System consists of multiple interacting computational entities known as agents. These agents possess two essential capabilities: they can act autonomously, meaning that they make independent decisions to fulfil their objectives, and they can interact with other agents in meaningful ways. This interaction extends beyond simple data exchange and encompasses behaviours such as cooperation, coordination, and negotiation, similar to human social interactions. Operating in dynamic environments, agents adjust their internal states and behaviours in response to changes in their environment to achieve individual or collective goals (Wooldridge, 2009).

A MAS is inherently robust due to its distributed nature; if one agent fails, others can often continue functioning, making it well-suited for real-world applications such as synchromodal transport and container terminal operations. In these contexts, agents dynamically adapt and optimise operations like container stacking and shipment planning, to hopefully maximise efficiency across the transportation planning and container terminals. MAS has been widely applied in logistics and container terminals, where it has proven effective in various aspects such as yard crane and automated guided vehicle (AGV) scheduling (Chen et al., 2020; Hu et al., 2021), transshipment planning (Abourraja et al., 2017), and container handling and stacking optimisation (Rekik & Elkosantini, 2019; Y. Zhang et al., 2024).

A conceptual overview of a MAS where both a synchromodal transport planning agent and a stacking optimisation agent can communicate is given in Figures 3.7 and 3.8. These figures show the network from the STPP-FS that is utilised and illustrates the stacking operations for each node. Figure 3.8 is further created to illustrate the synchromodal transport planning agent as the central orchestrate which interacts with the ten nodes in the network represented by terminal agents. In this system the planning agent focused on scheduling routes and shipments in a synchromodal manner. The terminal agent will focus on ensuring an efficient stacking strategy given the requests from the planning agent.

Agent Types

Wooldridge (2009) categorises agents into three types based on their decision-making approaches. These intelligent agents perceive their environment and act rationally to achieve their goals (Figure 3.9). Deductive reasoning agents rely on formal logic to derive conclusions from a set of premises, ensuring consistency in decision-making. Practical reasoning agents, on the other hand, operate based on goals and plans, taking actions that are aligned with their objectives. Finally, reactive and hybrid agents integrate both reactive responses and deliberative approaches, adapting to dynamic environments effectively (Wooldridge, 2009). In the proposed MAS framework for this research, two primary agents are considered: the planning agent and the terminal agent. Identifying the appropriate classification for these agents is essential to structuring their decision-making processes effectively.

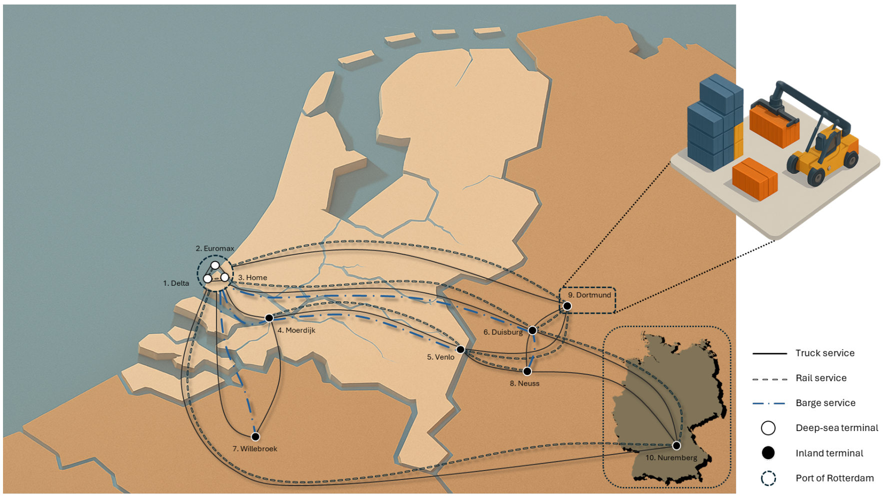


Figure 3.7: Illustration of the multi-agent system network.

Note. Author's creation.

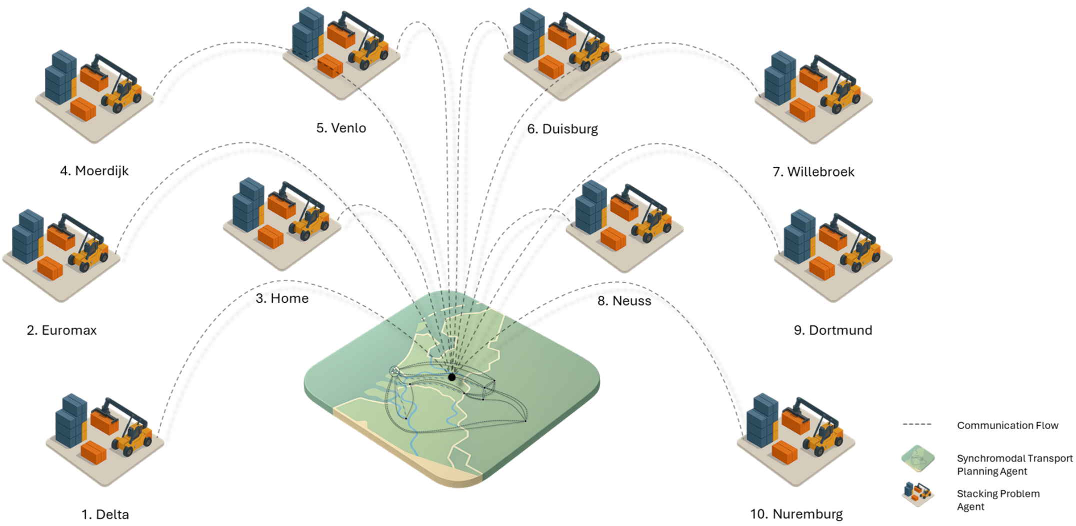


Figure 3.8: Illustration of the multi-agent system approach.

Note. Author's creation.

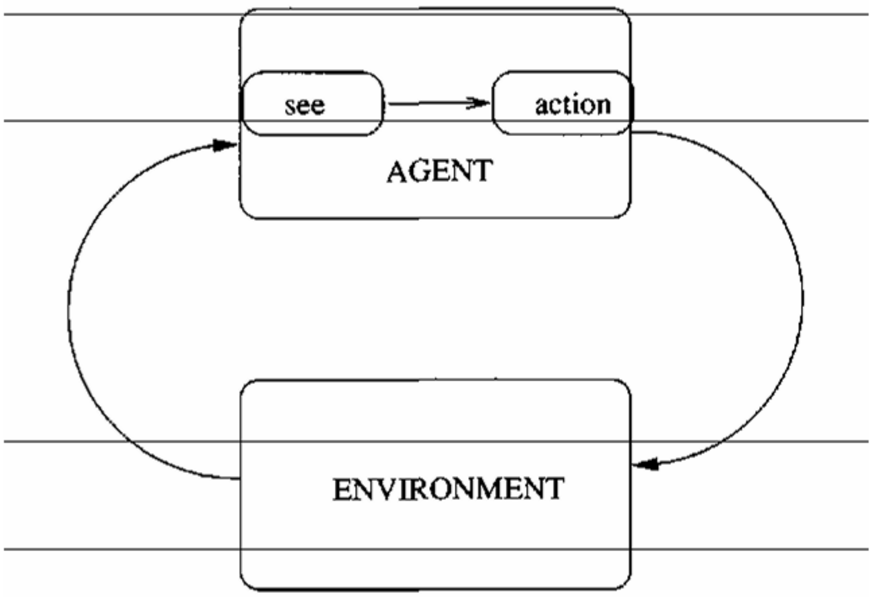


Figure 3.9: Perception and action of an agent in its environment.

Note. Reprinted from (Wooldridge, 2009).

Synchromodal Transport Planning Agent
The synchromodal transport planning agent is responsible for developing and executing transportation plans, ensuring efficient and adaptive logistics. It determines the most suitable transport mode by considering factors such as cost, efficiency, and sustainability. By continuously planning and adjusting shipment schedules across different modes, the agent responds dynamically to disruptions such as delays, congestion, and operational changes. Since this agent must evaluate alternative strategies, reason about future states, and optimise transport decisions in real time, it aligns best with the classification of a practical reasoning agent. Such agents deliberate about their goals and formulate structured plans to achieve them, making this category a natural fit for the role of a synchromodal transport planner.

Container Terminal Agent
The container terminal agent operates at a node where containers are loaded, transshipped, and unloaded. Its decision-making is driven by immediate environmental factors, such as container priority, available storage capacity, and real-time terminal conditions. Unexpected events, such as late arrivals or sudden congestion, require rapid responses to maintain efficiency within the terminal. Given that this agent primarily reacts to incoming information without engaging in complex long-term planning, it is best classified as a reactive agent. Reactive agents function by responding directly to environmental changes rather than reasoning about future scenarios.

Multiagent Interactions
Multi-agent interactions involve encounters where agents collaborate, compete, or negotiate (Figure 3.10). Cooperative interactions involve agents working together toward a common goal, Optimising overall system efficiency. Competitive interactions arise when agents pursue conflicting objectives, often requiring strategic decision-making to outmaneuver opponents. Negotiation-based interactions occur when agents communicate and bargain to achieve mutually beneficial agreements, balancing individual and collective objectives (Wooldridge, 2009).

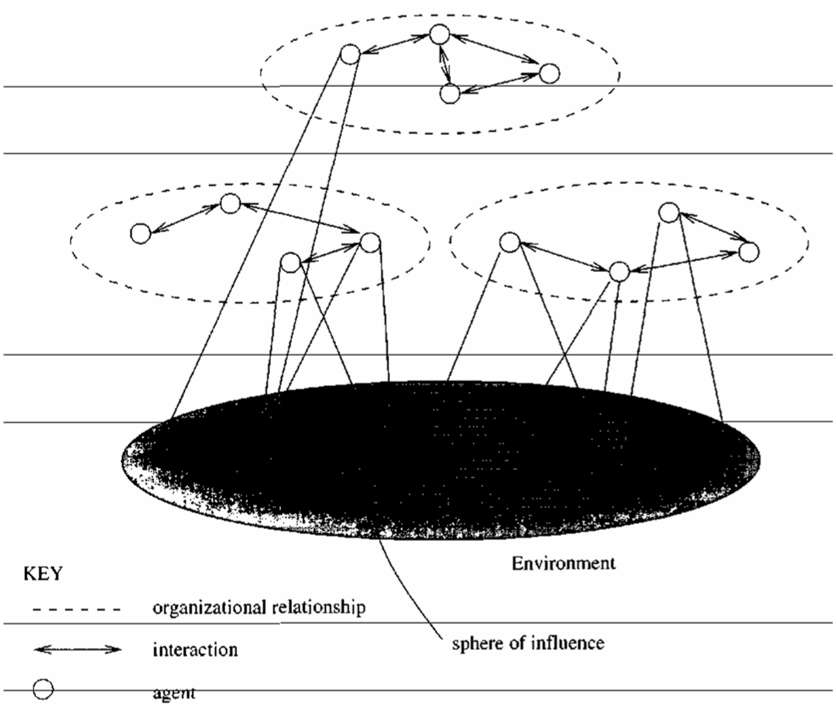


Figure 3.10: Typical structure of a multi-agent system.

Note. Reprinted from (Wooldridge, 2009).

Between the now identified practical reasoning- and reactive agents there will be interactions. Given that the MAS could also consist of multiple synchronised transport planning agents and multiple container terminal agents. Wooldridge (2009) identified three types of encounters where agents collaborate, compete, or negotiate. Within the logistic sector there are a lot of different dynamics, with competition and negotiation between actors all being likely interactions since businesses usually have to compete against each other.

There are of course exceptions in real-life where LSPs or shipping company actively work together in for example so called alliances. With 2M for Maersk and the Mediterranean shipping company, the Alliance consisting of Hapag-Lloyd, HMM, Yang Ming, and Ocean Network Express, and Ocean Alliance consisting of CMA CGM, OOCL, Cosco and Evergreen being the three biggest and most well-known alliances for ocean transport. In the MAS this could be mimicked if multiple planning agents where to exist and with some of them working together. In the MAS this can be solved by choosing to have a synchromodal transport planner represent an alliance that competes against or negotiates with other agents or alliances.

Collaboration between LSPs and container terminals or between container terminals is also not completely out of the picture. For ocean liners it is quite normal to have a (majority) stake in or ownership of container terminals for their benefit. For example, APM Terminals, a company of the AP Moller Maersk Group, holds stakes or ownership in over 50 ports and container terminals around the globe and COSCO Shipping has the same in over 30 terminals (APM Terminals, 2023; COSCO SHIPPING Ports Limited, 2024). To add to this APM Terminals and COSCO Shipping share ownership in a number of terminals among which terminals in Belgium, China, Egypt, and Italy (APM Terminals, 2023; COSCO SHIPPING Ports Limited, 2024). Showing that these companies work together on the terminals side without being in the same alliance for the shipping operations side. Also in the Dutch hinterland it is not uncommon that different inland terminals are under the same ownership, the Kennisinstituut voor Mobiliteitsbeleid (KiM), the Dutch Institute for Transport Policy Analysis, made an overview of the inland container terminals in the Netherlands in 2019 (Figure 3.11), this listed all terminals amongst them several under the same parent name like BCTN or BTT (Visser & Francke, 2019).

Figure 3.11: Container terminals (accessible to third parties) in the Netherlands.

Note. Reprinted from (Visser & Francke, 2019). Translation: Zeehaven = Seaport; Toekomstig = Future.

Competition and negotiation between LSPs and container terminals can of course arise when there is a single LSP with a request from A to B that can both be served by two different terminals wherein the terminals compete with each other and negotiation with the LSP. What this section has hopefully shown so far is that the interactions within a supply chain can vary a lot between LSPs and container terminals causing them to be quite complex as the number of agents increases. For example when considering structures used by Maersk and COSCO Shipping with collaboration on the terminal operations on one side and competition between their alliances on the shipping side.

Going back to the purpose of this study, that is trying to asses the impact of synchromodality on container terminal, it is not a necessity to model all these complex interactions. The model should represent synchromodal transportation, but not necessarily all the different possibilities in which synchromodal transportation could arise from the different interaction angels derived from the structures between the agents. According to Table 3.4 the MAS should focus on the collaboration across stakeholders. Giusti et al. (2019) proposed a Fifth-party logistics (5PL) service provider as a ”synchromodal service orchestrator”. Using this ”orchestrator” approach could already greatly reduce the complexity of the interactions between synchromodal transport planning agent, by accepting that this orchestrator could represent a number of planning agents that are connected to the 5PL platform for this study.

This single orchestrator would then only have to have continuous updates from the related container terminals in order to be able to create and replan a synchromodal transport plan. The necessary information that needs to be collected from the container terminals would be related to the logistical costs for handling and storage and the state of a terminal which helps the orchestrator to create the best plan. The remaining interaction between the orchestrator and the container terminals would be a collaboration interaction. The 5PL orchestrator aims to foster collaboration across stakeholders, maximising flexibility, cost and time optimisation, and environmental sustainability. Meanwhile, the container terminal's task is to provide accurate feedback while maintaining efficient operations.

Dependence Relations

The previous paragraph described the interactions between the synchromodal transport planning- and container terminal agents in the to be developed MAS as a collaborative interaction. Dependence relations describe how agents rely on one another to achieve their goals. The dependence between the types of agents can be classified into four types, interdependent, unilateral dependent, mutual dependent, or reciprocal dependent. In interdependent settings, agents act independently without needing support from others. In unilateral dependence, one agent relies on another to achieve a goal, but the reverse does not hold. Mutual dependence occurs when two agents depend on each other for the same goal, reinforcing collaboration. Reciprocal dependence describes a scenario where each agent relies on the other for distinct objectives, ensuring that their goals are met through cooperative interactions (Wooldridge, 2009).

Given the collaborative interaction setup between the agents in the MAS the two most logical dependence relations would be mutual- or reciprocal dependence. If the assumption is made that container terminals connected to a 5PL platform should act in a way that it benefits the overall objective of the 5PL service provider there would be a great argument for a mutual dependence relationship. However the more likely situation would be that LSPs or container terminals join a 5PL platform for their own benefit. Suggesting that both types of agents depend on each other in order to optimise their own objective.

This dependence can be explained by the following examples. Assume that a synchromodal planning agent develops an initial schedule that routes several shipments through the same terminal simultaneously. This influx of containers can overwhelm the terminal, leading to inefficient stacking and longer dwell times. Such operational issues can render the original transport plan infeasible, resulting in delay penalties. If the container terminal agent monitors these conditions and communicates potential saturation risks back to the planning agent in real time, the planning agent can then adjust the schedule, either by dispersing shipments over different time slots or selecting alternative routes to optimise operations and mitigate delays.

Mechanism Design and Reaching Agreements

Mechanism design is a critical aspect of Multi-Agent Systems, governing how agreements are formulated and maintained. Effective mechanisms ensure guaranteed success, where an agreement is always reached, and strive to maximise social welfare by Optimising the collective utility of all agents. Pareto efficiency is achieved when no alternative outcome can make an agent better off without disadvantaging another. Individual rationality ensures that agreements are in the best interest of participating agents, while stability encourages adherence to agreed strategies. Simplicity in negotiation protocols ensures ease of understanding and implementation, while a well-designed distributed system reduces single points of failure and minimises communication overhead (Wooldridge, 2009).

Designing an agreement-reaching mechanism for the MAS requires balancing feasibility, efficiency, and robustness. In a distributed logistics environment, ensuring that planning decisions remain viable for all stakeholders while maximising overall efficiency is a key challenge. A distributed approach offers a compelling solution, as it eliminates single points of failure and reduces inter-agent communication overhead. By decentralising the agreement process, each agent retains autonomy while collectively contributing to an optimised plan. This enhances resilience and adaptability, ensuring that planning remains feasible across all participating terminals.

To complement this distributed approach, the principle of Pareto Efficiency provides a strong guiding criterion. A plan is considered Pareto efficient if no alternative allocation can improve at least one participant's outcome without negatively impacting another. This ensures that the final agreement is not only feasible but also optimally balanced across all agents, preventing inefficient allocations that could hinder operational performance. By integrating a distributed decision-making framework with Pareto-efficient outcomes, the mechanism fosters both robustness and fairness. Each terminal remains capable of autonomously evaluating and accepting feasible plans while collectively striving for the most beneficial solution. This approach ensures that planning decisions remain both practical and performance-driven, aligning with the broader objectives of a 5PL strategy.

3.3. Data Sources & Requirements

For the multi-agent simulation setup, data is necessary. This includes information on shipments requests, barge and train service schedules, and terminal configurations. Since this research builds on the study from Y. Zhang et al. (2022a), its information on shipments and shipment schedules can be taken as a starting point. Y. Zhang et al. (2022a) presents different sets of requests and works with a transport network inspired by European Gateway Services (EGS) in the Rhine-Alpine corridor introduced in Y. Zhang et al. (2022b), which is visualised in Figure 3.4.

Request Data

The request data created by Y. Zhang et al. (2022a) is detailed in Table 3.10 showing the number of requests to be planned, the number of unique departure and arrival nodes, the plan horizon in hours and the total number of containers of all requests. Each of these requests originates from the Delta, Euromax, or Home terminal and moves into the hinterland toward one of seven inland terminals. From the perspective of the STPP-FS the complexity increases as the number of requests increases, the complexity from the perspective of the SP increases as the number of total containers increases.

Table 3.10: Request datasets.

Requests	Departure Nodes	Arrival Nodes	Plan Horizon	Total Containers
5	3	2	192	92
10	1	5	159	220
20	3	5	168	397
30	3	7	168	646
50	3	7	185	1,039
100	3	6	189	1,930
200	3	7	191	4,099
400	3	7	191	8,054
700	3	7	224	8,021
1,000	3	7	228	7,937
1,300	3	7	213	7,988
1,600	3	7	199	7,790

Note. Derived from (Y. Zhang et al., 2022a).

Services & Schedules

The setup for this research is based on the EGS network shown in Figure 3.4. In this network, there are three modes of transport, barge, train, and truck, for which the routes of barge and train can be fixed or flexible depending on the settings. Table 3.11 shows the different types of services that are considered. It is important to note that the capacity of a truck emulates the number of trucks rather than the number of containers that can be transported on a single truck.

Table 3.11: Service types.

Type	Fleet Size	Capacity	Speed	c1	c1’	c4
Barge	49	160	15	0.6122	0.0213	0.2288
Train	33	90	45	7.540	0.0635	0.3146
Truck	34	1,000	75	30.98	0.2758	0.8866

Note. Derived from (Y. Zhang et al., 2022a). c1: Transport cost per hour per container; c1’: Transport cost per km per container; c4: Carbon tax coefficient per ton

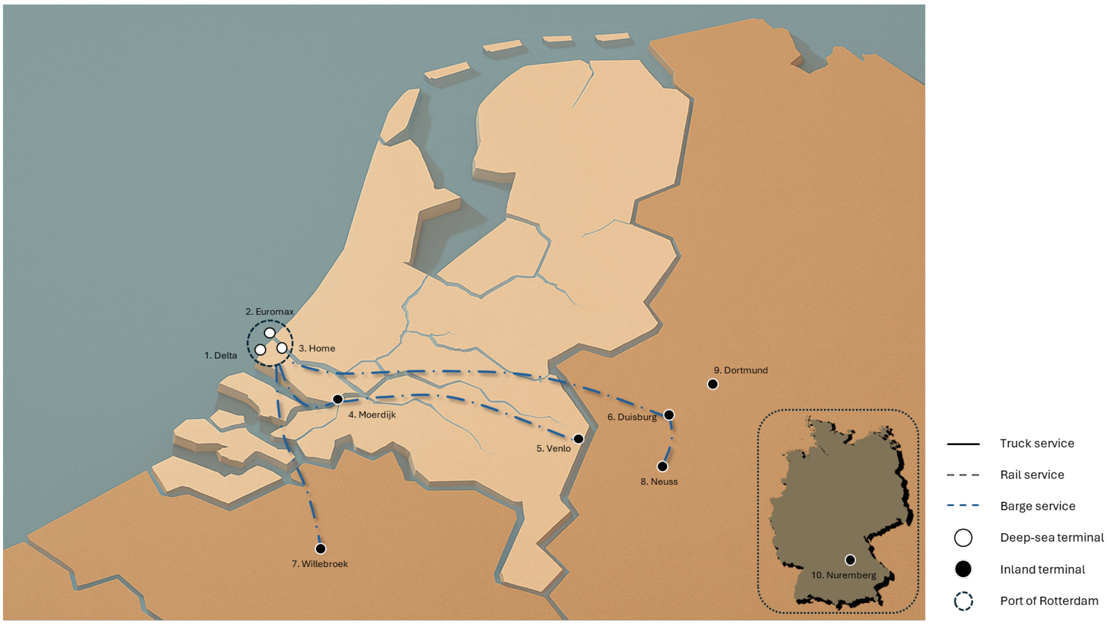


Figure 3.12: Illustration of barge services in the multi-agent system.

Note. Author’s creation. Adapted from (Y. Zhang et al., 2022a).

The fixed services are illustrated in Figures 3.12 through 3.15 and the detailed service schedules are given in Tables A.1 through A.3 for barges, trains and trucks respectively. In these tables a fixed service between two terminals is noted as follows: *[arrival time at start node] - [departure time at start node] →[arrival time at end node] - [departure time at end node] [service number]*. In case barges are allowed to execute flexible services, each barge service will originate from the same start terminal and terminate at the same end terminal. Truck services do not have any fixed services, Table A.3 shows the combination of start and end nodes for the truck service where they will originate and end.

3.4. Experimental Setup & Model Development Process

The development of the Multi-Agent System begins with an in-depth technical examination of two key models. First, the STPP-FS from Y. Zhang et al. (2022a) is analysed using its original Python implementation. This step provides insight into the model’s structure, input parameters, and output characteristics, serving as a foundation for integration with other components. Second, the SP formulation from Expósito-Izquierdo et al. (2015) is reconstructed, starting with the mathematical model before implementing the heuristic solution. This reconstruction facilitates a detailed understanding of how container stacking operates in its fundamental form and allows for linking its inputs and outputs to those of the

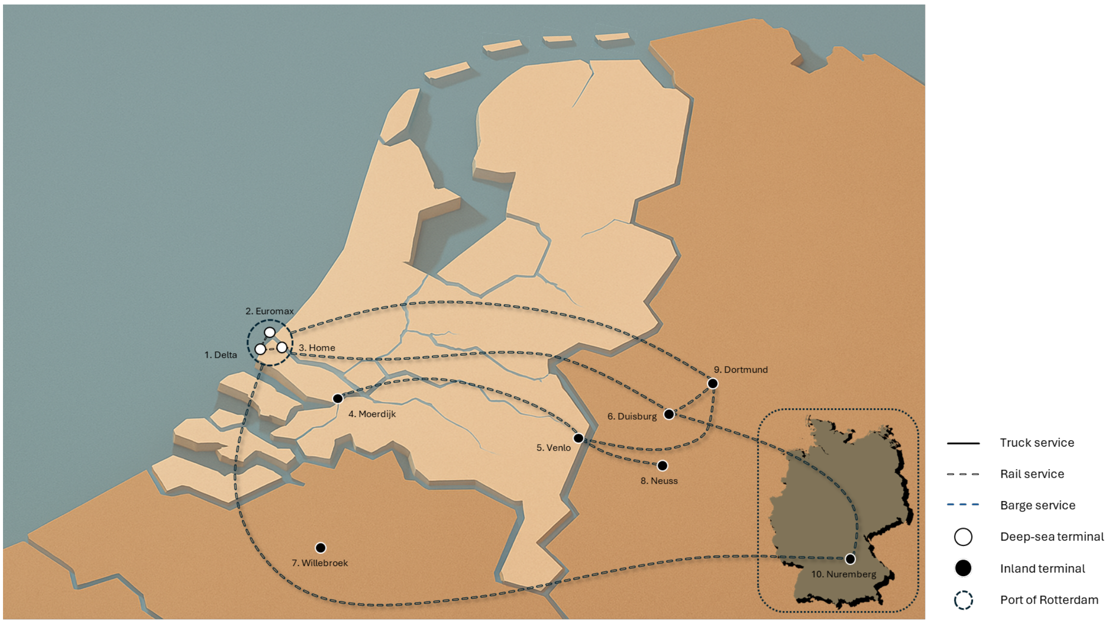


Figure 3.13: Illustration of train services in the multi-agent system.

Note. Author's creation. Adapted from (Y. Zhang et al., 2022a).

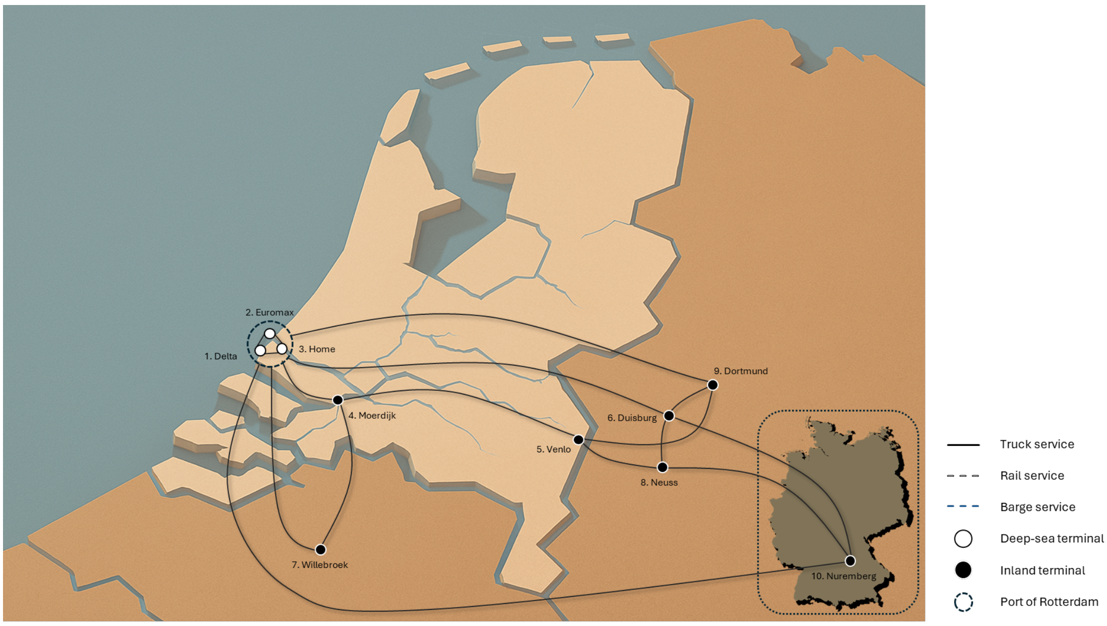


Figure 3.14: Illustration of truck services in the multi-agent system.

Note. Author's creation. Adapted from (Y. Zhang et al., 2022a).

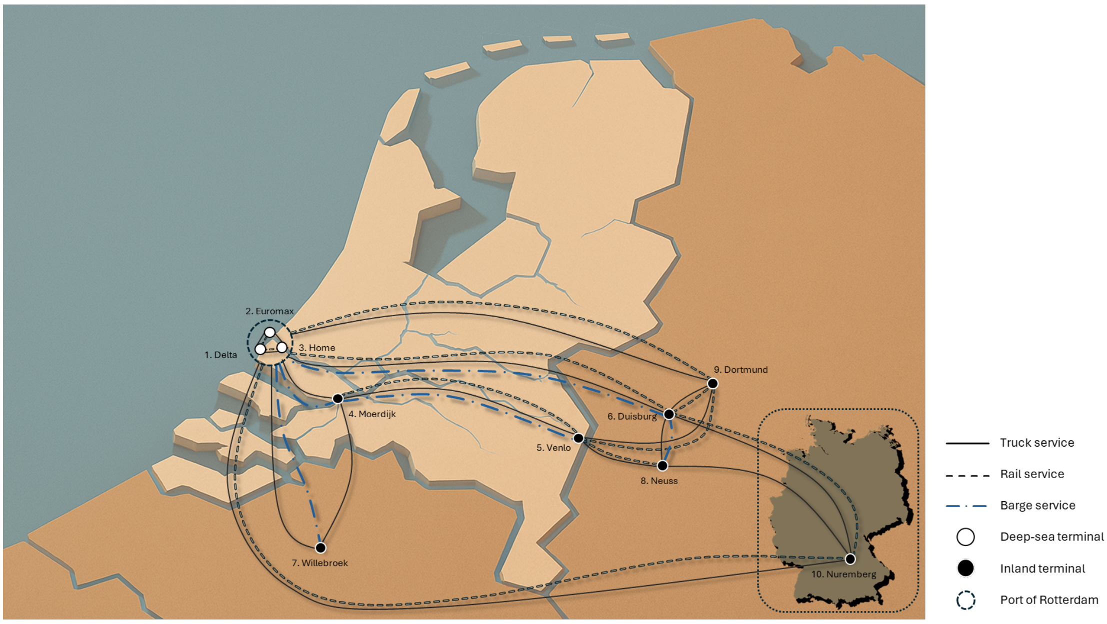


Figure 3.15: Illustration of all services in the multi-agent system.

Note. Author's creation. Adapted from (Y. Zhang et al., 2022a).

STPP-FS.

3.4.1. Model Adaptations

To better align the STPP-FS and SP with terminal operations, modifications are introduced to reflect real-world constraints. The models are extended to include different container types, such as perishable goods, which require specialised handling. Additionally, for the SP storage areas are defined to accommodate different transport modes, ensuring a more realistic representation of container flow within a terminal. These enhancements transform the original stacking model into a framework that more accurately captures the complexity of terminal operations.

3.4.2. Multi-Agent System Integration

The integration of the STPP-FS and SP into a MAS follows a two-stage process. In the first stage, the planning agent, based on the STPP-FS, generates an initial transport plan. This plan is then assessed by terminal agents, which represent the adapted stacking model. Each terminal agent evaluates the feasibility of the proposed transport schedule based on key performance metrics, including excess dwell times for vehicles and the percentage of feasible actions at the terminal. The outcome of this stage is a go/no-go verdict, where terminal agents determine whether the transport plan is executable within the given constraints. Terminal performance is further assessed by tracking the number of relocations required to accommodate the plan.

In the second stage, terminal agents provide feedback on the transport plan, allowing the planning agent to iteratively adjust the scheduling until all terminal agents approve the proposed solution. This iterative process ensures that not only feasibility but also optimisation is considered. Additional metrics are introduced to evaluate improvements in planning efficiency, including the percentage of planned transport requests, total planning costs, and the impact on overall terminal operations. Terminal performance is further assessed based on the total number of actions required, the number of transshipments, and the extent of relocating. By refining the transport plan through multiple feedback loops, the system moves towards a solution that balances operational feasibility with efficiency.

Table 3.12: Evaluation metrics for stage 1.

Category	Metric
Planning Performance	Excess dwell times for vehicles at terminals
	Percentage of feasible actions at terminals
Terminal Performance	Number of relocations

Table 3.13: Evaluation metrics for stage 2.

Category	Metric
Planning Performance	Excess dwell times for actions at terminals
	Percentage of feasible actions at terminals
	Percentage of planned requests
	Total planning costs
Terminal Performance	Number of relocations
	Total number of actions
	Total number of transshipments

3.5. Evaluation & Validation Approach

The evaluation and validation of the proposed Multi-Agent System are conducted in multiple stages. Since adaptations are to be made to the Stacking Problem heuristic, the first stage of evaluation focuses on assessing the computational impact of these modifications. While a direct one-to-one comparison with the original heuristic is not feasible due to the introduction of additional features, it remains essential to quantify the increase in computational complexity. This analysis provides insight into the trade-off between added functionality and the resulting computational costs.

The second stage of evaluation compares the performance of the original STPP-FS model with the fully integrated Multi-Agent System. This comparison serves to quantify the additional complexity introduced by replacing the passive terminal nodes in the STPP-FS with active agents representing terminals through the adapted Stacking Problem model. By analysing these differences, it becomes possible to assess the impact of decentralised decision-making and increased inter-agent coordination on system performance.

The validation of the model is integrated with the scenario analysis conducted as part of the third research sub-question. In this analysis, various disruptions in container transportation are simulated to examine the system's response and adaptability. Potential scenarios include, equipment failures at ports leading to decreased throughput and increased handling times, and mode service failures, thereby restricting transport routes. By evaluating how the planning and terminal agents respond to these disruptions, the model's ability to adapt to real-world uncertainties is assessed. The results of these scenarios are analysed to determine whether the behaviour of the system is consistent with expectations, ensuring that the adjustments made by the agents are rational and operationally meaningful.

3.6. Limitations & Assumptions

The developed model is a simulation-based approach that leverages existing methodologies for STPP-FS and the SP to assess the impact of synchromodality on container terminals. While this provides valuable insights at macro and meso levels, it remains a simplification of reality. The primary objective is to evaluate how terminals can become overloaded in specific scenarios and how this, in turn, influences supply chain performance.

3.6.1. Synchromodal Transport Planning Problem with Flexible Services

A potential limitation is that the STPP-FS model is largely adopted without modifications or refinements. The focus of this research is more shifted towards adapting the SP and integrating it into the MAS. Any potential improvements identified during the research process will be incorporated when possible, or else documented as recommendations for future work.

In addition, there are more recent advances in the STPP-FS model. Y. Zhang et al. (2023) introduced a reinforcement learning module that enhances the original model and ALNS heuristic by dynamically replanning in response to unexpected events. This approach integrates real-time information across multiple transport modes, including road, rail, and inland waterways, making it particularly suitable for assessing synchromodal impacts. However, adapting this reinforcement learning framework in addition to setting up a MAS increases complexity. To ensure the feasibility of model development within the available timeframe, this study adopts the simplified dynamic replanning algorithm proposed in Y. Zhang et al. (2022a), enabling a functional MAS to be developed for scenario analysis, including replanning, albeit without the reinforcement learning component.

Finally, Section 3.2 suggested adding different container types in order to recreate more realistic container terminal situations. This will be adapted in chapter 4 for the SP, however, the STPP-FS will operate under the assumption that vehicles will have sufficient available capacity for each possible container type. Whereas in reality vehicles have limited capacity for certain container types, for example with reefer containers for which only limited power connections are available on a barge or train, this will not be adapted in the STPP-FS.

3.6.2. Stacking Problem

The SP presents several limitations that have been previously introduced. The primary limitation is that the original SP represents a container stack, rather than a container terminal. The adaptations proposed in this study aim to extend its applicability by incorporating terminal-like characteristics, such as container types and storage areas. However, at its core, the model remains a Stacking Problem rather than a full terminal simulation.

This distinction is important when considering performance analysis at different levels of granularity. The adapted SP facilitates a higher-level abstraction of terminal operations, enabling an MAS-based evaluation of synchromodal planning. However, if the goal were to conduct a detailed micro-level analysis of terminal performance, a more sophisticated terminal-specific model would be required. The chosen approach balances the level of detail necessary for meaningful analysis with computational efficiency, ensuring that the MAS can be implemented within the available time constraints.

3.6.3. Multi-Agent System

One of the key limitations of the MAS is the absence of monetary or cost-based decision-making in the terminal selection process when creating a route. The planning agent does have information on the costs of storage or operations on a terminal, but those are fixed. In this approach, terminals do not compete based on pricing strategies, but instead are assumed to maximise throughput by accepting transport requests whenever capacity is available.

This assumption simplifies the interaction between agents, ensuring that planning decisions primarily focus on feasibility rather than economic optimisation. While this approach aligns with the objective of assessing synchromodal system performance, it does not capture potential financial incentives or pricing mechanisms that might influence terminal choice in a real-world setting.

3.7. Conclusion on Methodology

This chapter presents the research methodology used to study the impact of synchromodal transport on inland container terminals. A Multi-Agent System was chosen to capture the autonomous and interactive nature of logistics stakeholders. Two key agents were defined: the planning agent, modelled using the STPP-FS by Y. Zhang et al. (2022a), and the terminal agent, represented by the SP model from Expósito-Izquierdo et al. (2015). The STPP-FS allows flexible planning with real-time re-routing, while the SP model supports efficient container stacking using idle time. Together, these models address both transport and terminal-side dynamics. The MAS facilitates real-time coordination and stakeholder collaboration, with a 5PL-style orchestrator simplifying interactions. These combined methods form the foundation for evaluating synchromodal strategies under realistic operational conditions. The next chapter discusses the model implementation and specific adaptations.

4 Model Development

This chapter presents the technical development of the models used in this research. The focus is on three key components: the Synchromodal Transport Planning Problem with Flexible Services, the adapted Stacking Problem, and the Multi-Agent System that integrates them. Each section outlines the necessary modifications, computational aspects, and integration steps to ensure a functional simulation framework.

4.1. Development of the STPP-FS Model

The STPP-FS model is taken from Y. Zhang et al. (2022a) and serves as the foundation for the planning agent within the MAS. Although no substantial modifications are made to its core methodology, it must be decomposed into input and output components that enable effective communication between the planning and terminal agents.

4.1.1. Decomposition of Input and Output Components

The input data for the STPP-FS were briefly discussed in Section 3.3. This section discussed the data sources & requirements, showing the request data (Table 3.10), the available service types (Table 3.11) and the service schedules (Tables A.1, A.2, A.3). For the decomposition of the input components, the request data should be explained in more detail.

Table 4.1: Request data example.

p	d	ap	bp	ad	bd	qr
Delta	Willebroek	62	110	62	110	13
Home	Moerdijk	116	164	116	164	13
Delta	Moerdijk	44	68	44	68	30
Delta	Moerdijk	73	97	73	97	24
Euromax	Moerdijk	120	192	120	192	12

Note. Created by the author based on (Y. Zhang et al., 2022a). ***p**: Pickup node; **d**: Delivery node; **ap**: Start pickup window at pickup node; **bp**: End pickup window at pickup node; **ad**: Start delivery window at delivery node; **bd**: End delivery window at delivery node; **qr**: Quantity of containers in request*

Table 4.1 shows an example of five requests that can serve as input data for the STPP-FS. Each request includes information on the pickup and delivery nodes, associated time windows, and the number of containers to be transported. As discussed under limitations and adaptations, the absence of container types is a limitation. To address this, the STPP-FS can be adapted by adding a container type to each request, such as general, reefer, empty, or hazardous containers. While these types do not affect transport-side planning in this study, they help simulate realistic terminal operations. For simplicity, it is assumed that each vehicle has sufficient capacity for each container type, even though, in reality, space is limited for specialized containers like reefers.

After the STPP-FS has finished with the creation of a transport planning, it outputs two main files. The first file named the best routes file outputs an excel file with a tab for each vehicle with its route. A route has the following structure as shown in Table 4.3. This example shows a route of a vehicle that originates at node *0* and terminates at node *6*. At time *35* it starts its route by loading two Request at node *0*. Request *100001* is picked up at this node with the service time starting at time *35* and ending at time *35.1* resulting in a service time of *0.1* hours. Request *100002* is also picked up at this node, but this is a transshipment pickup, meaning that this request originated from a node elsewhere and was brought here before by another vehicle. The service time for loading request *100002* starts right after the pickup for request *100001* has ended. After the pickup for these requests has ended the vehicle moves towards node *6*, where the delivery of the requests takes place. The example shows two types of deliveries being a transshipment delivery (Td), meaning that the request will have to move on to its final delivery node by other means of transport, and a normal delivery for request *100002*. After delivery is completed the vehicle terminates at its end depot node.

Table 4.2: Best route example of *'Barge1'* vehicle.

	begin_depot	**100001pickup**	**100002Tp**	**100001Td**	**100002delivery**	**end_depot**
0	0	0	0	6	6	6
1	35	35	35	47	47	47.5
2	35	35	35.1	47	47.2	47.5
3	35	35.1	35.3	47.2	47.5	47.5

Note. Created by the author based on (Y. Zhang et al., 2022a).
Row 0: *Indicates the node;* ***Row 1:*** *Indicates the arrival time;* ***Row 2:*** *Indicates service start time;* ***Row 3:*** *Indicates service end time which if relevant equals departure time*
pickup: *Indicates pickup from original pickup node;* ***Tp:*** *Indicates pickup from transshipment node;* ***Td:*** *Indicates delivery to transshipment;* ***delivery:*** *Indicates delivery to final delivery node*

Next to the best routes file the STPP-FS outputs a routes match file. This file shows on overview of all requests that were offered to the STPP-FS and what vehicles they use as shown in Table 4.2. Taking the information from Table 4.3 into account the routes match data shows that request *100001* and *100002* both share a transport leg on *Barge1*. Request *100001* is transferred onto *Train1* towards it final node, whereas request *100002* is picked up using *Truck2* before being transferred onto *Barge1*.

Table 4.3: Routes match example.

	100000	**100001**	**100002**	**100003**	**100004**	**100005**
0	Truck1	Barge1	Truck2	Train2	Barge2	Barge2
1		Train1	Barge1	Truck3		Truck4
2						

Note. Created by the author based on (Y. Zhang et al., 2022a).
Row 0: *Indicates the first vehicle;* ***Row 1:*** *Indicates the second vehicle;* ***Row 2:*** *Indicates the third vehicle*

The information from these two files is eventually structured into a dictionary that shows all the requests that should be loaded, transferred, or unloaded for each terminal as shown in the Listing B.1 in Appendix B. The outer dictionary contains the node id relating to a specific terminal. Within this there is an inner dictionary for each request relevant to this node. This inner dictionary contains relevant information on the quantity, delivery window, pickup window, container type, and the inbound and outbound vehicle. In case a request originates from a terminal it has no known information on its delivery action. Therefore, the delivery window times are set to *-1* and the inbound vehicle to *None*. In case a request terminates at a node, it is the opposite, now the pickup window is set to *-1* and the outbound vehicle is set to *None*.

4.1.2. Development of Dynamic Sequential Service Times

The original STPP-FS model uses fixed parallel service times. This means that regardless of the amount of requests and their respective quantities, loading or unloading this onto a single vehicle would take the exact same time. Given that the STPP-FS communicates the loading and unloading windows to the SP, this can cause unrealistic practices. To address this, changes have been made to the STPP-FS to allow for request-based service times and sequential loading. Table 4.2 already shows this in an example where the service time for *100002Tp* starts after service for *100001pickup* has been completed. The request-based service time is calculated by default by multiplying the related quantity by a service time per container. This service time per container can be further specified by making them specific per terminal and or mode.

4.2. Development of the Stacking Problem

The Stacking Problem serves as the foundation for modelling terminal operations. The existing model, as proposed by Expósito-Izquierdo et al. (2015), requires modifications to represent container terminal operations rather than a pure stacking process. In addition, it must be structured to receive output data from the STPP-FS. This section details the enhancements made to the SP and their computational implications.

4.2.1. (Restructure Output of STPP-FS

The STPP-FS output has to be structured so that the SP can use it. The SP needs to have the following data that is an id for a container (often similar to its departure time), its arrival time and its planned departure time. This allows for the model to reason such as depicted in Figure 4.1. On the left are the incoming containers at times *17, 24, 28, and 31* and on the right the already retrieved containers at times *3, 5, 9, 15*.

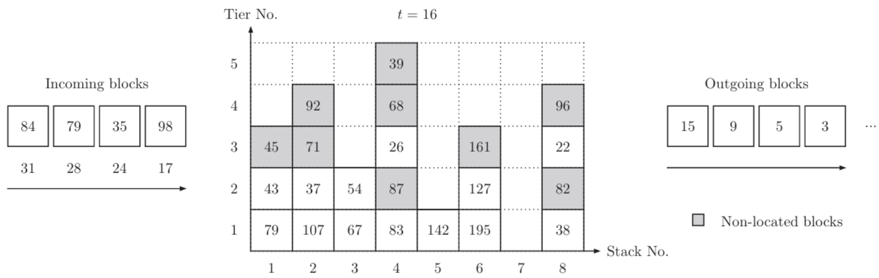


Figure 4.1: Overview of stacking problem stacks.

Note. Reprinted from (Expósito-Izquierdo et al., 2015).

Structuring the output of the STPP-FS so that it can be used for the SP requires a couple of steps. The first thing that stands out and needs to restructured is that the STPP-FS is request-based whereas the SP is container-based. One of the first steps is then to expand each request in such a way so that there is an id, arrival time, and departure time for each container. The previous section also discussed the introduction of planning using sequential service times rather than fixed parallel service times. This approach allows for a more accurate estimate of the service times since request can vary in size for example. Table 4.4 shows the restructured output of the STPP-FS.

Table 4.4: Restructured output of STPP-FS.

container_id	request_id	delivery_start	delivery_end	pickup_start	pickup_end	reefer	empty	hazardous	inbound	outbound
100001.000	100001	-1	-1	35.00	35.10	False	False	False	None	Barge1
100001.001	100001	-1	-1	35.00	35.10	False	False	False	None	Barge1
...	...	...	...	...	...	...	...	...	...	...
100001.008	100001	-1	-1	35.00	35.10	False	False	False	None	Barge1
100001.009	100001	-1	-1	35.00	35.10	False	False	False	None	Barge1
100002.000	100002	-1	-1	35.10	35.30	False	False	False	Truck2	Barge1
100002.001	100002	-1	-1	35.10	35.30	False	False	False	Truck2	Barge1
...	...	...	...	...	...	...	...	...	...	...
100002.016	100002	-1	-1	35.10	35.30	False	False	False	Truck2	Barge1
100002.017	100002	-1	-1	35.10	35.30	False	False	False	Truck2	Barge1

4.2.2. Modelling Terminal Operations

As mentioned in the research methodology this model does have a few limitations that need to be addressed to get the most out of its implication. The following limitations have been identified:

- Duplicate priorities
- Handling capacity and Time synchronisation
- Container types
- Single storage area and storage type

Duplicate priorities

Some stacking models can handle multiple containers that arrive or depart at the same time. The STPP-FS from Section 3.2.3 also works in the manner of planning requests which consists of multiple containers, so they arrive in batches. For this SP Heuristic to accept duplicate priorities of containers a few small changes have to be made. Inherently the SP Heuristic does not explicitly support duplicate priorities nor excludes this possibility. A non-located container c' is defined as being stacked above c with the retrieval time of c' being greater than c. If the retrieval time is equal this will not be counted as an incorrectly stacked container. Further the attractiveness calculation from Equation 3.1 also assumes that containers with the same retrieval time can be stored above each other.

There is one drawback to this SP heuristic with its way of working with duplicate priorities. That is if multiple containers are to be retrieved at the same time this will all happen in a single iteration, without being able to trace which movement was performed first and how many total movements were made. In other words, there is no strict limit on the number of movements per timestep during loading or unloading. During the improvement strategy, there is however a limit of one relocation movement per timestep, so this causes a skewed dynamic.

Given the output from the STPP-FS is structured as in Table 4.4, the following changes have been made. In Algorithm 4, $D_c(t)$ was formerly defined as *'Set of containers to release (inbound) in time t'* and $R_c(t)$ was formerly defined as *'Set of containers to retrieve (outbound) in time t'*. In the extended version (Algorithm 4), this is now defined as the set of containers to be released or retrieved for which the service time of its arriving or departing vehicle is started.

Algorithm 4 Updated SP solver algorithm.
Note. Adapted from Expósito-Izquierdo et al., 2015.

for $t = 0 \rightarrow H - 1$ **do**
  $D_C(t) \leftarrow$ Set of containers to release for which $delivery - time \geq t < pickup - time$
  $R_C(t) \leftarrow$ Set of containers to retrieve for which $delivery - time \geq t < pickup - time$
  if $R_C(t) \neq \emptyset$ **then**
    for $c \in R_C(t)$ **do**
      for $c' \in O(c)$ **do**
        $s \leftarrow$ Select target stack for c' according to Eq. (4.1)
        Relocate c' in s
      Retrieve c from the top of its stack
  if $D_C(t) \neq \emptyset$ **then**
    for $c \in D_C(t)$ **do**
      $s \leftarrow$ Select target stack for c according to Eq. (4.1)
      Place c in s
  if $D_C(t) \cup R_C(t) = \emptyset$ **then**
    Reduce the number of non-located containers by using the improvement strategy

Handling Capacity and Time synchronisation
The times provided by the STPP-FS are given in hours, based on that input the SP has been given a handling capacity per hour. Based on this handling capacity the start and end (horizon) times provided by STPP-FS are extended on to make sure the time is linearised, movements are limited to one per linearised timestep to ensure every movement is executed sequentially and it can be monitored accordingly. As an example, if a terminal has a handling capacity of four, it can perform a movement between hour one and hour two at these times: $\{1.00, 1.25, 1.50, 1.75, 2.00\}$.

Container Types
Another characteristic of the SP heuristic is the absence of multiple container types. Although this simplification is not uncommon in stacking problems, real-life situations often involve multiple container types. Although container types are standardised, they can vary depending on their application. In terms of size, containers range in length from 20 feet to 45 feet and also differ in height, with the standard height and high-cube variants being the most common.

The STPP-FS considered only a single container type. However, there are three notable container variants in terms of their storage requirements for which the SP heuristic will be extended. The first is the regular, non-empty container, which can typically be stored in almost any location within a terminal. The second variant is the empty container, which can either be stored in dedicated empty stacks—where Last-In-First-Out (LIFO) practices can be applied, ensuring proper placement—or alongside regular non-empty containers. Lastly, reefer containers require specialised storage areas equipped with cooling capabilities to maintain the necessary conditions. In the next part the dedicated storage areas for empty and reefer containers will be touched upon further.

Single storage area, storage types and equipment type
A fairly big limitation of the Stacking Problem is that it is usually solely focused on a single storage area. For this research, the purpose of the SP is to accurately model an inland container terminal. The inland container terminals generally have multiple storage areas in their terminal, for example, dedicated to empty or reefer containers. Next to that these storage areas might also be caused by physical limitations and their unique layout. In a terminal, there is limited space next to the quay wall or train tracks. So a separate storage area is created more inland of the terminal to create more capacity. Shunting operations are then necessary to move containers between these stacks. Figures 4.2, 4.3, 4.4, and 4.5 show areal views of some inland terminal in the hinterland of the Port of Rotterdam, this gives an idea of the unique layout these terminals have and how different storage areas are formed.

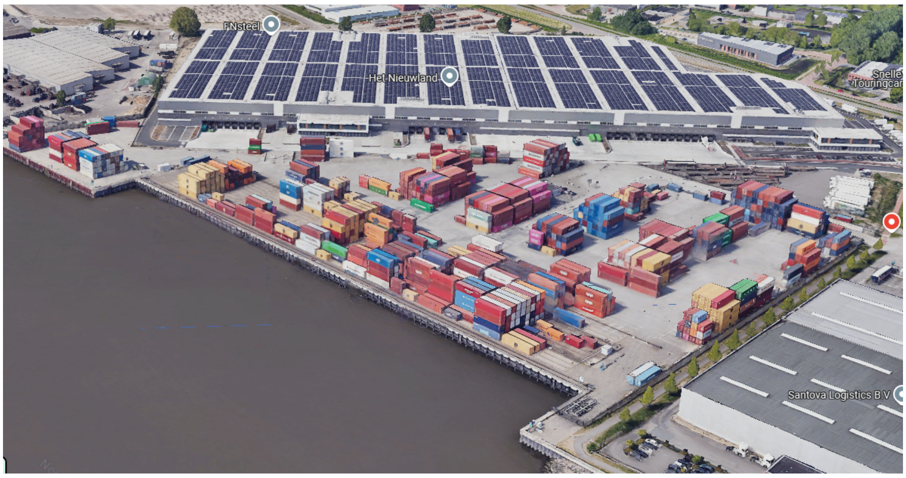


Figure 4.2: Aerial view of BCTN Alblasserdam, as seen on Google Maps.

Note. Source: Google Maps (Google, n.d.). Available at https://www.google.com/maps.

Figure 4.3: Aerial view of Barge Terminal Tilburg, as seen on Google Maps.

Note. Source: Google Maps (Google, n.d.). Available at https://www.google.com/maps.

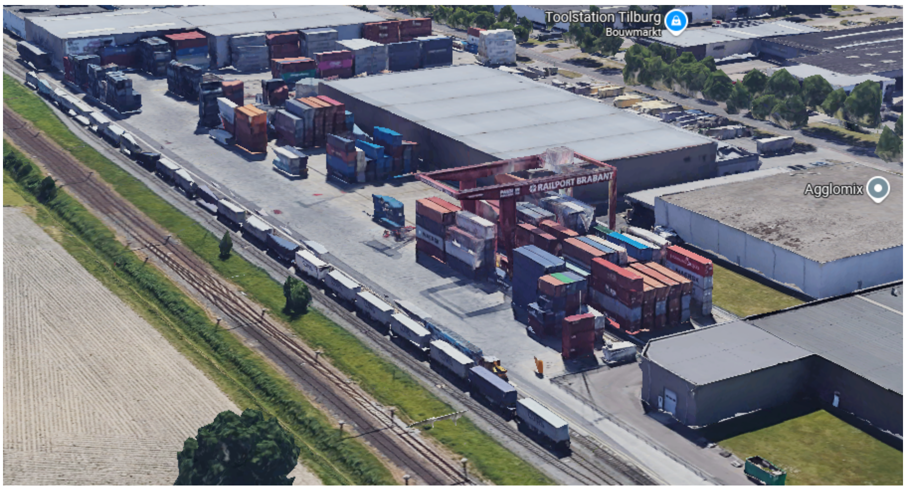


Figure 4.4: Aerial view of BTT Railport Brabant, as seen on Google Maps.

Note. Source: Google Maps (Google, n.d.). Available at https://www.google.com/maps.

Figure 4.5: Aerial view of CTT Almelo, as seen on Google Maps.

Note. Source: Google Maps (Google, n.d.). Available at https://www.google.com/maps.

Based on these images and a general understanding of how terminals should operate the following storage areas are defined in Table 4.5. In this table, three columns are used to describe the area's capabilities. The 'Container Types' column shows why type of containers can be stored in each area. The Equipment column shows what type of equipment can be used to retrieve containers from that specific area. Finally, the 'Modalities' column shows which modalities can be unloaded or unloaded directly from that stack. Figure 4.6 is created to give a visual example of how these storage areas may look in a terminal.

Table 4.5: Storage areas.

Storage Area	**Container Types**	**Equipment**	**Modalities**
Barge Gantry Storage	■ Non-Empty ■ Empty ❏ Reefer	■ Gantry Crane ❏ Reach Stacker	■ Barge ❏ Train ■ Truck
Barge Gantry Buffer Storage	■ Non-Empty ■ Empty ❏ Reefer	■ Gantry Crane ■ Reach Stacker	■ Barge ❏ Train ■ Truck
General Container Storage	■ Non-Empty ■ Empty ❏ Reefer	❏ Gantry Crane ■ Reach Stacker	❏ Barge ❏ Train ■ Truck
Empty Container Storage	❏ Non-Empty ■ Empty ❏ Reefer	❏ Gantry Crane ■ Reach Stacker	❏ Barge ❏ Train ■ Truck
Reefer Container Storage	❏ Non-Empty ❏ Empty ■ Reefer	❏ Gantry Crane ■ Reach Stacker	❏ Barge ❏ Train ■ Truck
Train Gantry Storage	■ Non-Empty ■ Empty ❏ Reefer	■ Gantry Crane ❏ Reach Stacker	❏ Barge ■ Train ■ Truck
Train Gantry Buffer Storage	■ Non-Empty ■ Empty ❏ Reefer	■ Gantry Crane ■ Reach Stacker	❏ Barge ■ Train ■ Truck

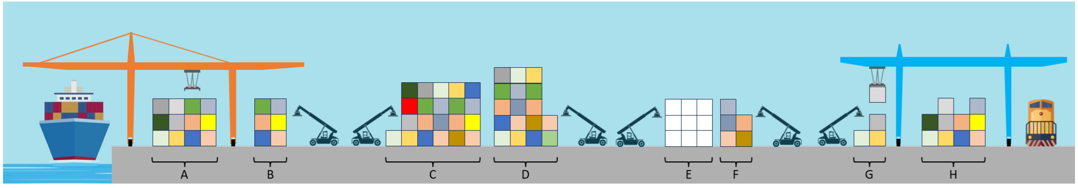


Figure 4.6: Schematic side view of storage areas in an inland terminal.

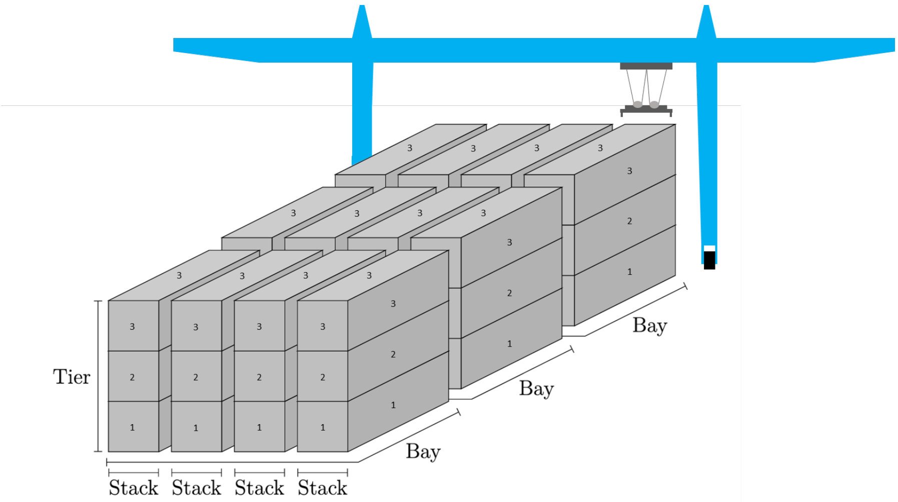
Note. Author's creation. A = Barge Gantry Storage, B = Barge Gantry Buffer Storage, C = General Container Storage, D = Empty Container Storage, E = Reefer Container Storage, F = Hazardous Container Storage, G = Train Gantry Buffer Storage, H = Train Gantry Storage.

To get these storage areas into the SP heuristic a few changes have to be made. First of all each storage are will have to be assigned its container types, equipment, and modalities that it can serve. Next, it is important to understand how the equipment influences stacking operations. The original SP heuristic assumes that each stack and bay can be accessed from above, for the storage areas that can be accessed by gantry train this logic still stands, meaning that a container can be placed in a tier above another container. However, for the storage areas that cannot be accessed by gantry crane and solely rely on placing containers using a reach stacker they can only be accessed from the side. Meaning that the container can only be retrieved if its access via a reach stacker is not blocked by another stack of containers in the same bay. Figure 4.7 is created to better understand this reasoning, where Figure 4.7a shows the setup for the gantry cranes and Figure 4.7b shows that for the storage areas accessible by reach stackers. In this image the term 'tier' previously used to describe the stacking height is now replaced with 'rank'. When placing a container in a stack or bay it will be placed in the lowest available 'rank'.

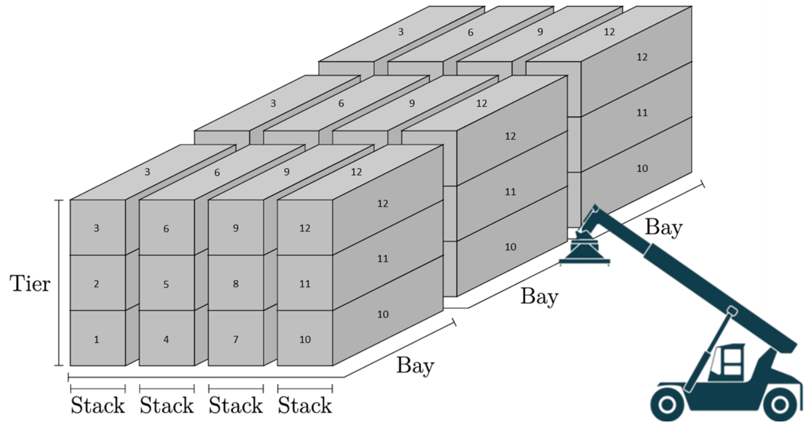
In the case of the empty stack storage, it behaves similarly to that of a storage area equipped with a reachstacker when it comes to placing containers. With the exception being that the retrieval follows a LIFO approach. Meaning that when an empty container is supposed to leave the terminal the first available container is taken from the stack. In the SP heuristic extension, this is solved by adding a piece of code that relocates the containers in each bay in such a way that the containers are sorted perfectly according to their priority. Ensuring that the empty container with the highest rank is always the first to be retrieved.

A final thing that needs to be discussed for the SP heuristic with multiple storage areas is how they affect the attractiveness of stacks. The attractiveness of a stack is calculated according to Equation 3.1, which calculates the attractiveness of stack s for container c. The effect of the implementation of container types will be that the set of stacks S passed to the Equation will be filtered beforehand according to the requirements. As an example if c is a reefer container then s is in a set of stacks that can facilitate reefer storage. In the case that c is an empty container, s is in a set of stacks that can store empty containers. Since this set of stacks contains storage space in the dedicated empty stack which has the LIFO policy the attractiveness for those available slots needs to be calculated differently. The attractiveness of placing an empty container c into a dedicated empty container slot is set to r_c. This means that it is as attractive as placing the container onto another container which leaves at the exact same time. The updated attractiveness calculation is shown in Equation 4.1.

$$f(c,s) = \begin{cases} \infty, & h(s) = nT \\ r_c, & empty(s) = True \\ K, & h(s) = 0 \\ \min(s) + \frac{h(s)}{nT}, & 0 < h(s) < nT \wedge \min(s) \geq r(c) \\ 2K - \min(s) + \frac{h(s)}{nT}, & 0 < h(s) < nT \wedge \min(s) < r(c) \end{cases} \tag{4.1}$$



(a) Container stacking ranks for gantry crane.

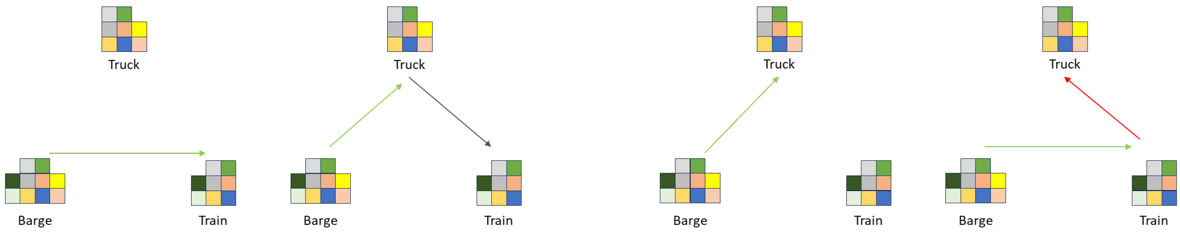


(b) Container stacking ranks for reach stacker.

Figure 4.7: Container stacking ranks for equipment types.

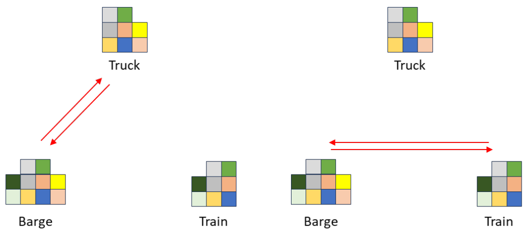
Note. Author's creation based on (Boschma et al., 2023).

Apart from the attractiveness being influenced by the container types, it is also influenced by the shunting or in-yard movements. These are the movements of containers between different stacks. Sometimes these movements are inevitable for example when a container arrives by barge and leaves by train, the container will have to move inside the yard since the is no storage area that can directly service both modalities. This should massively influence the attractiveness of stacks near the quayside or the rail track. If the container is directly moved from one side of the terminal to the other or if this movement is performed last minute it is still the same in-yard movement. The interesting thing happens when there are extra in-yard movements, for example ,if the same container is first moved to the general storage area, which is only directly accessible for trucks, and then later to the rail side, resulting in one extra movement. Figure 4.8 is created to show how extra in-yard movements are determined for this research. This same logic can be applied if a container is already stored in a certain area and then moved again towards any other area.



(a) Inbound or current storage: Barge, outbound: Train.

(b) Inbound or current storage: Barge, outbound: Truck.



(c) Inbound or current storage: Barge, outbound: Barge.

Figure 4.8: In-yard movements, with extra in-yard movements indicated by red arrows.

Note. Author's creation.

To determine how these extra in-yard movements influence the attractiveness of stacks in different storage areas is a difficult endeavour. But in a simplified way it is dependent on the number of extra movements and the amount of time left before it gets picked up again or more specifically the number of handlings that a terminal can perform during that time. The assumption here is that the attractiveness of a stack for container c in a storage area that would require an extra in-yard movement is penalised heavily if c is about to be retrieved relatively soon, but not hardly so when its retrieval time is far in the future. With the available idle time during this time being available to reposition this container in time again to its preferred position. This effect will be modelled with a logistic decay function as shown in Equation 4.2. Here λ_c equals the number of handlings available before retrieval, ρ_s is the number of extra in-yard movements for container c to stack s, and α is a scaling parameter. The behaviour of function $p(c,s)$ will look like Figure 4.9, showing a penalty value between two for low $\lambda(c)$ to $\rho(s)$ ratio towards one for a higher $\lambda(c)$ to $\rho(s)$ ratio. The final attractiveness is thus calculated as $f(c,s) \cdot p(c,s)$.

$$p(c,s) = 2 - \frac{1}{1 + e^{-\alpha(\frac{\lambda(c)}{\rho(s)} - \beta)}} \tag{4.2}$$

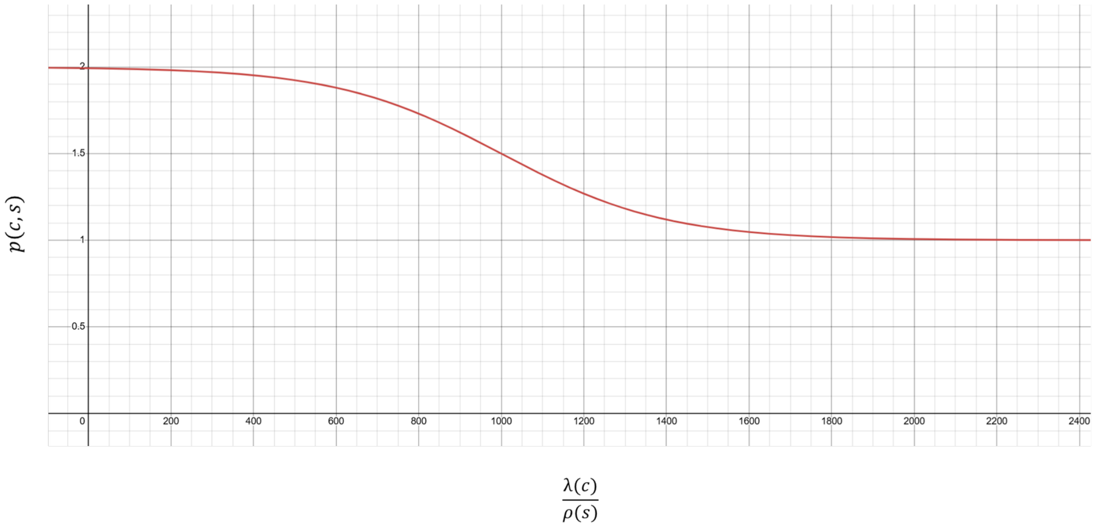


Figure 4.9: Example of decay function $p(c, s)$, with $\alpha = 0.005$ and $\beta = 1{,}000$.

For the remainder of this study, the following parameter values are used: $\alpha = 0.005$ and $\beta = 1{,}000$. In practice, this function primarily impacts containers that are scheduled for retrieval within the next 1,000 handlings. Given that the total number of containers in the simulation does not exceed 8,000, this represents a sufficiently large time window to allow for repositioning where necessary. For example, transshipment containers that must depart by barge will be considerably more attracted to stacks near the quay if they are due for pickup within this timeframe. Because this penalty only affects containers with imminent retrieval, it is unlikely to lead to relocation complications. Rather, it acts as a final tie-breaking factor in the attractiveness evaluation.

It is important to note that the goal of this addition is not to fully model in-yard movement complexity, but to ensure that such movements are at least acknowledged in the attractiveness score. As such, this logistic decay function serves as a pragmatic adjustment rather than a central modelling feature. The topic of in-yard movements—and especially the interactions between multiple storage yards—is acknowledged here for completeness but will not be explored further in the remainder of this study.

4.2.3. Terminal Configuration

The network used by Y. Zhang et al. (2022a) for the STPP-FS, consists of ten nodes in the hinterland of Rotterdam. In the MAS these nodes will be represented as terminals by the SP, in reality these terminals will have different layouts and capacities. The MAS utilises a terminal configuration file which is passed down to a specific terminal. This configuration is made possible by the developments on the modelling of terminal operations and the time synchronisation. The default capacities for each terminal are decided on using the data requests information from the STPP-FS. The terminals all have a capacity that is at least greater than the maximum number of containers that originate or terminate from that terminal for each request configuration.

In total five different terminal configurations have been made, they will be referred to as terminal configuration A through E. Terminal configuration A is the configuration with the lowest capacities and is used for request sets 5 trough 30, where the total number of containers is at most 646. Terminal configuration B, C, and D are specifically made available for request set 50, 100, and 200, with capacities in line with the information from Table 3.10. Finally terminal request E is made for request set 400 through 1,600 as the total number of containers is equal amongst these sets.

The handling capacities for each terminal are aligned with the size of each terminal and with the original STPP-FS. Since the STPP-FS is adapted from parallel loading and unloading to sequential loading and unloading, but none of the other parameters like the vehicle service are updated, it is important that the handling capacity is sufficient so that the parallel loading activities can still be in line with the rest of the model parameters. The details of terminal configurations A through E are shown in Appendix C in Tables C.1 through C.5.

In the remainder of this research and specifically in Chapter 5: Results & Analysis, two different approaches are used when it comes to terminal configuration. Since part of this study wants to see how the size of container terminals can affect the influence of synchromodality has on those terminals. Therefore, the analysis uses two types of terminal configuration setup. These are the Size-Adapted Configuration (SAC) and the Fixed-Maximal Configuration (FMC). In the SAC the terminal configurations are adapted in relation to the size of the request, thus terminal configuration A is the configuration is used for request sets 5 through 30, terminal configuration B, C, and D are used for request set 50, 100, and 200, and terminal configuration E is used for all the greater request set. In the FMC all request sets use terminal configuration E, this allows for a thorough examination of how terminal configuration affects synchromodal influence for requests sets 5 through 200.

4.2.4. Container Slot and Type Assignment

In the STPP-FS request have to be transported from one terminal to another, meaning that they have to originate from somewhere. In the terminal where the originate from they have to be retrieved from the stack, but therefore they need an allocated slot in the first place. At the start of each stacking assignment, an initial slot is allocated for every container at its origin terminal. This is done as follows each stack is assigned a random stack and bay. After this is completed all the containers in in the same stack and bay are sorted according to their retrieval time in order to determine the tier and their eventual slot. This means that each stacking assessment starts with correctly stacked containers, they are however not optimally stacked. That would include for containers to stacked in such a way that their retrieval times are also very close to each other, which is not guaranteed with this assignment.

Another thing to discuss is the type assignment for each container. The introduction of container types and different storage areas is mainly interesting because the terminal will have a dynamic of multiple storage areas instead of a single big one. The STPP-FS does not consider any container types and can therefore also not really communicate about this information with the terminal agents. To avoid possible conflicts between containers and their types in terminals that cannot be controlled by the planning agent, the container types are randomly determined in proportion to the amount of available space for a specific container type at each terminal. Thus when a request of twenty containers enters a yard, each of those containers has a probability of being any type of container. If this same request enters a different yard, they container types are reassigned for that specific terminal. This is not an ideal realistic application of the different container types, but it does allow for different storage areas to exist without having to alter the STPP-FS.

4.3. Development of the Multi-Agent System

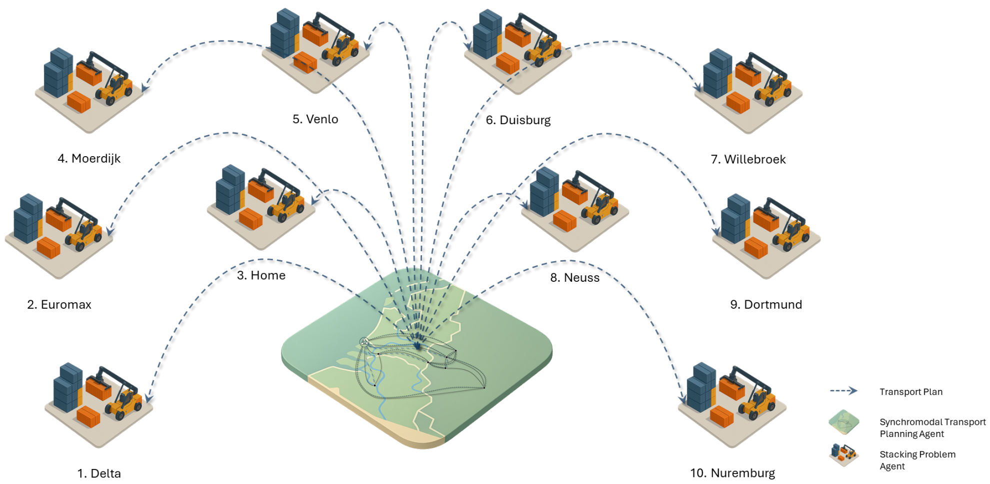
The MAS is developed in two stages. Initially, a passive communication system is established, where the planning agent generates a transport plan and terminal agents respond with feasibility feedback. In the second stage, active communication is introduced, enabling terminals to provide feedback that iteratively improves planning feasibility.

4.3.1. First Stage: Passive Communication

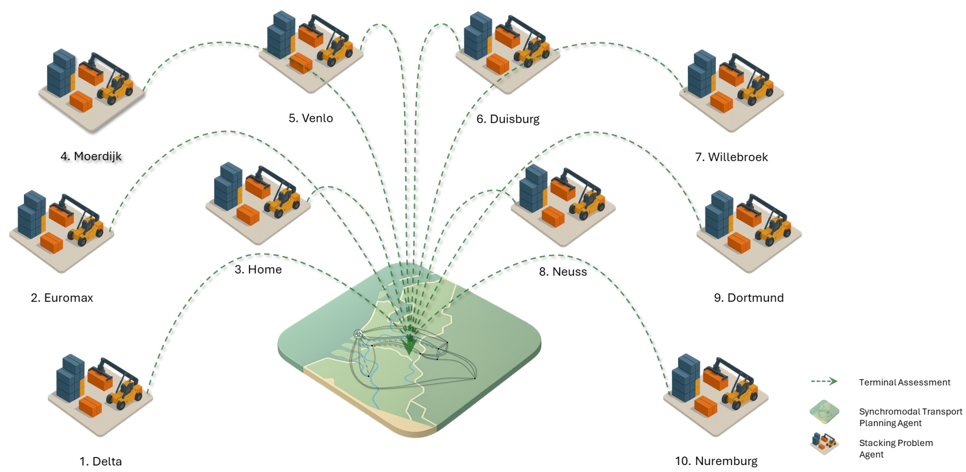
The first stage of the MAS development focuses on establishing a structured information flow from the STPP-FS, from now onwards referred to as the planning agent, towards the Stacking Problem, from now onwards referred to as the terminal agent, as illustrated in Figure 4.10. This stage serves as the foundation for enabling coordination between transport planning and container stacking. The implementation is developed in Python 3.9.12, and its structure is illustrated in Algorithm 5.

This algorithm outlines the main components and data flow within the MAS framework. The planning agent first generates a transport plan based on a specified request set. After execution, relevant data is retrieved, including shipment details, best routes, and route matches. These outputs are structured into a format suitable for terminal operations. Next, terminal agents for different terminals are initialised using this structured data. Each terminal agent (e.g., Delta and Nuremberg) sets up its requests, slot allocations, and parameter settings. Once initialised, the agents execute their main operations sequentially, simulating the stacking process at each terminal.

Finally, the framework analyses dwell and delay times by tracking the action times for each vehicle and the pickup and delivery action's execution time and planned end time per request. This information is recorded to assess the efficiency of the stacking operations and to support future optimisations in the MAS framework. Tracking dwell and delay times of vehicles allows for a little bit more leniency towards the planning, if multiple actions are planned for a vehicle at a terminal. If one action takes longer than expected it can be compensated by an action that takes shorter than expected. Tracking dwell and delay times for each request allows for a more thorough review of the transport planning.



(a) Transport plan communication flow.



(b) Terminal assessment feedback flow.

Figure 4.10: Visual example of first-stage multi-agent system development.

Note. Author's creation.

Algorithm 5 MAS Framework - Stage 1.

```
Initialise planning agent
Create planning agent and generate shipment plans
Retrieve Planning Data
Extract shipment data, best routes, and route matches from the planning agent
Structure Planning Output
Process and structure data into terminal requests
Initialise terminal agents for Terminals
for each terminal do
    Create terminal agent with terminal requests
    Set up requests, slots, parameters, and variables
Execute MAS
for each agent in MAS do
    Run agent operations
Analyse Dwell and Delay Times per Vehicle
for each agent in MAS do
    for each action do
        Retrieve latest action time and planned end time
        Record dwell and delay information
Analyse Dwell and Delay Times per Request
for each agent in MAS do
    for each delivery action do
        Retrieve latest action time and planned end time
        Record dwell and delay information
    for each pickup action do
        Retrieve latest action time and planned end time
        Record dwell and delay information
```

Vehicle Delay

Regarding the feasibility check from terminals there are different options regarding how one classifies a plan as feasible. The most reasonable way of thinking would lead to think that a plan is feasible if there is no vehicle delay at a terminal. When assessing the vehicle delay, all the actions of a vehicle at all terminals are considered in chronological order. The vehicle delay was previously mentioned to allow for some leniency because the actual service times of multiple requests can compensate for each other. This same logic could potentially also be applied for actions at different terminals. The argument can be made that a small delay at terminal A could be compensated by the service time at terminal B, assuming there would be some extra time margin over there and most importantly if the related vehicle has a flexible service. This where the idea of the running delay is introduced. Running delay is calculated as the sum of delays for a vehicle if it has flexible service. One could argue that as long as the running delay is negative or equal to zero at the end of the route, the route could be deemed feasible. However the service time deviations are calculated based on the window wherein the shipments were supposed to be loaded or unloaded. Meaning that a substantial delay at terminal A results in substantial later start time at terminal B and therefore the service time deviation findings at terminal B are not representative. The first stage of the MAS records the following information after running in Table 4.6, for this example the maximum amount of service time delay that can be compensated between two terminals is set to 0.25 hours.

Table 4.6: Vehicle delay assessment.

Vehicle	Terminal	Service Time Deviation	Running Vehicle Delay	Verdict
Barge1	(1) Delta	0.20	0.20	Infeasible
	(5) Venlo	0.15	0.35	Positive running delay
Barge2	(1) Delta	0.05	0.05	Feasible
	(6) Duisburg	-0.20	-0.10	Negative running delay, marginal time compensation.
Train1	(2) Euromax	-0.10	0.00	Feasible
	(8) Neuss	-0.2	0.00	Fixed service, sufficient windows
Train2	(2) Euromax	0.01	0.00	Infeasible
	(9) Dortmund	-0.2	0.00	Fixed service, insufficient time window at Euromax
Truck1	(5) Venlo	-0.10	-0.10	Infeasible
	(6) Duisburg	0.2	0.10	Positive running delay
Truck2	(6) Duisburg	0.05	0.05	Feasible
	(8) Neuss	-0.2	-0.1	Negative running delay

4.3.2. Second Stage: Active Communication

In the second stage of the MAS development the focus is on developing a feedback loop from the terminal agents to the planning agent, learning from the findings from the first stage, as illustrated in Figure 4.11. This section will start off by discussing the difficulties in creating this feedback loop, followed by a proposed solution and finally this section will discuss the dynamic replanning setup that can be used for scenario analysis.

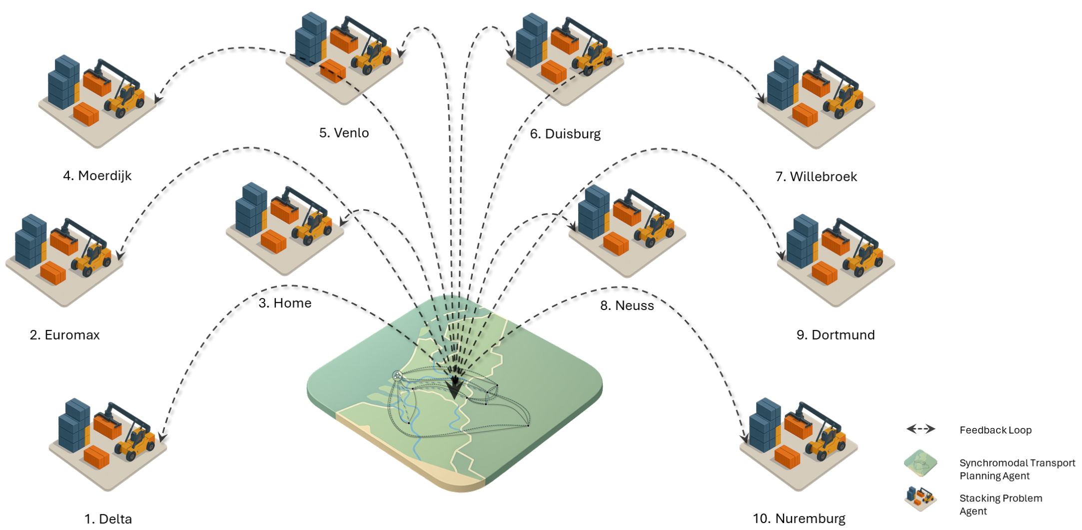


Figure 4.11: Visual example of second-stage multi-agent system development.

Note. Author's creation.

Feedback Loop

The simplest way to give the feedback is for the terminal agent to state to the planning agent that loading for Request X took 30 minutes longer than expected. This won't be sufficient however since the loading time for Request X took 30 minutes longer in this specific transport plan at this specific terminal in a given time window. Changing the service time of one request could cause a ripple effect causing the transport planning to change. The action for request X could be rescheduled to a different time or terminal on the same day, causing the initial observation of service time delay to not be representative. Even other shipments that could be replanned or rerouted causing the terminal state to be different, all causing the initial observed service time to be of less and less importance.

A single feedback point is insufficient to generate a new transport plan, and even multiple feedback points from a single plan provide only limited insight given the many factors that influence each planning. To obtain accurate service time estimates, multiple data points, patterns, or iterations are necessary to observe how agents behave under the current state. If certain terminals consistently experience high demand across multiple instances, the assumed service time should be adjusted accordingly. This information can then be leveraged to distribute terminal usage more efficiently across both space and time.

The concept of recording multiple data points and identifying patterns to predict service times aligns with the principles of demand forecasting, where past observations inform future planning. In the logistics sector, demand forecasting has been widely studied, focusing primarily on freight or customer demand to optimise resource utilisation, such as vehicle allocation (Nuzzolo & Comi, 2014; Powell, 1987), terminal equipment management (Yu et al., 2018), and port development for strategic planning (Alcalde et al., 2015). Other research has explored traffic pattern prediction, which has been applied predominantly in mobility studies but also in routing optimisation.

Hill and Böse (2016) presents a decision support system with an advanced forecasting engine that provides predictive analytics to logistic nodes as well as to collaborating truck companies. The proposed system provides forecasted truck arrival rates to the nodes and predicted truck gate waiting times at the nodes to the truck companies based on historical data. Based on the expected workloads, resources can be planned more efficiently. Truck companies can adjust their route planning in order to minimise waiting times. Consequently, both sides benefit from reduced truck waiting times while reducing traffic congestion and air pollution.

This approach of Hill and Böse (2016) is very interesting for this paper. On the one hand it predicts truck arrivals to logistic nodes such as empty container depots, packing facilities or terminals. These facilities can utilise this estimation of future workloads to improve their resource planning. On the other hand the estimated waiting times at these nodes are made available for truck companies that do business at these nodes. These are able to adjust their route planning in order to reduce the waiting times at the nodes. Translating this to the MAS this could be interpreted by the planning agent sharing the (initial) transport planning to the terminal agents, as well as the terminal agents sharing estimated service times to the planning agent for replanning in order to reduce waiting or delay times at terminals.

According to Hill and Böse (2016) the expected result of this optimisation-driven interplay is smoothed peak workloads at the nodes due to adaptive truck routing and reduced truck waiting times because of more accurate resource deployment at the nodes. Figure 4.12 shows an overview of how Hill and Böse (2016) modelled the forecasting setup, specifically the smoothed peak workloads step can help with gradually moving towards a feasible planning.

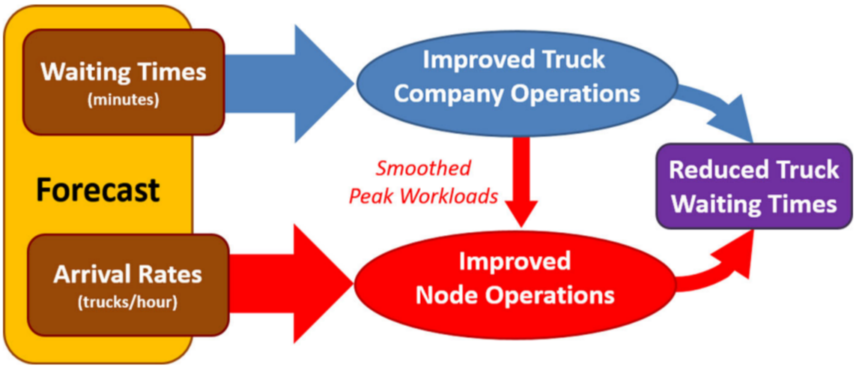


Figure 4.12: Benefits of forecast information on truck waiting times and arrival rates at logistic nodes.

Note. Reprinted from (Hill & Böse, 2016).

Figures 4.13 and 4.14 are representations of forecasts of waiting times. Applying this approach to the MAS is not as straightforward, this does not have any historical data available, so actual forecasting cannot be applied. However it is possible to run the MAS over a couple of iterations, with each iteration generating data about the observed service times. This iterative data can then be used to make better estimates of the service times to create a similar effect of the smoothed peak workloads. The decision is made to mimic forecasting patterns by having a few iterations in the MAS, which will allow it to collect multiple data points and highlight big demand patterns for the specific set of requests.

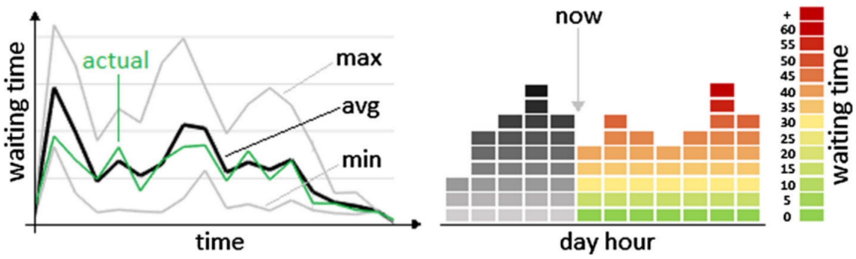


Figure 4.13: Waiting time forecast representations.

Note. Reprinted from (Hill & Böse, 2016).

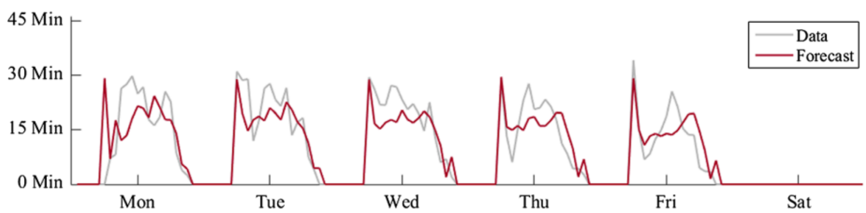


Figure 4.14: Forecasted hourly average truck waiting times versus historical data for the last week of the horizon.

Note. Reprinted from (Hill & Böse, 2016).

In order to do this a structure had to be developed that could store all the relevant data, in this case service time data. A service time matrix is introduced to the planning- and terminal agents for this purpose. This matrix is able to store all the service time data points in all of the dimensions, so time, space and the request based dimension next to that it will also make a distinction between loading and unloading actions.

By default a theoretical service time is appointed to each combination of the dimensions, this is necessary for the first iteration of the initial planning. This theoretical service time is based on the terminal configuration and its handling capacity per hour, which would be the lower bound for any action at that specific terminal. If a terminal has a handling capacity of 50 movements per hour and request X consists of 25 containers, loading or unloading at this terminal takes at least 0.5 hours or 30 minutes to complete. In order to make the model more likely to provide a feasible planning this theoretical service time can be increased a bit if the lower bounds are too strict. The decision to do this is a trade-off between performance and dwell time. The time synchronisation between the planning- and terminal agents is in hours, where fractions represent minutes and so on. To keep the matrix from having an excessive size service times are stored within the hour they are performed in. As an example if loading of Request X takes 1.5 hours at the Delta terminal starting at time 0.75 and ending at 2.25 a service time of 1.5 hours will be added to hours 0, 1, and 2. If loading takes only 0.9 hours between time 3 and 3.9, it is only added to time 3. Table 4.7 shows an example of how this matrix is structured and Figure 4.15 gives a visual representation of the service time matrix.

Table 4.7: Service time matrix setup.

Request	**Terminal**	**Time**	**Action**	**Observed Service Times**
Request X	(1) Delta	0	Loading	[0.5, 1.5, 1.5]
Request X	(1) Delta	0	Unloading	[0.5]
Request X	(1) Delta	1	Loading	[0.5, 1.5, 1.3, 1.5, 1.3, 1.4]
Request X	(1) Delta	1	Unloading	[0.5]
Request X	(1) Delta	2	Loading	[0.5, 1.5, 1.3, 1.5, 1.3, 1.4]
Request X	(1) Delta	2	Unloading	[0.5]
Request X	(1) Delta	3	Loading	[0.5, 0.9, 1.3, 1.3, 0.9]
Request X	(1) Delta	3	Unloading	[0.5]
...	...	...	...	[0.5]
Request Z	(10) Nuremburg	250	Loading	[0.8]
Request Z	(10) Nuremburg	250	Unloading	[0.8, 0.8, 0.86, 0.8, 0.9]

This service matrix is available for the planning agent to use to estimate service times. There are a couple of ways to use this information Figure 4.13 already shows an example with the minimum, average, and maximum observed values over times that can be used to create patterns. However, using these as estimated service times might not yield preferable results. Using the minimum will be too strict, resulting in infeasible planning, and using the maximum might be too lenient, causing too much dwell time. Using the average does offer a lot of good qualities, as when more and more data points become available, the average gradually shifts. However, there is still the possibility that the average is too strict. Therefore, the selected approach is to use the mean observed service time plus two standard deviations.

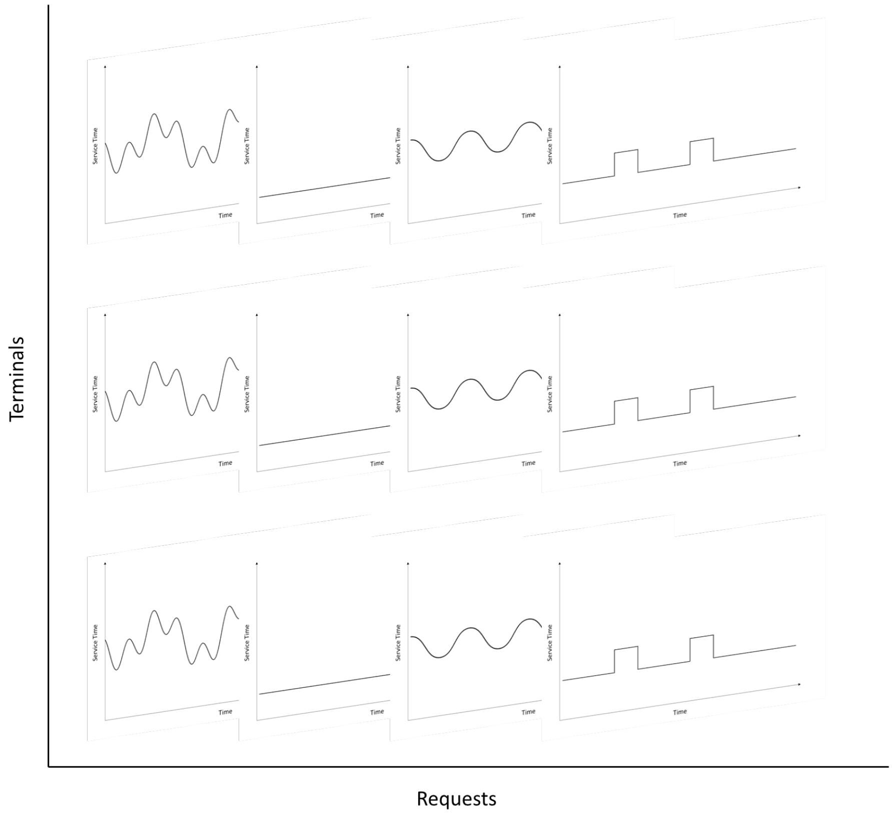
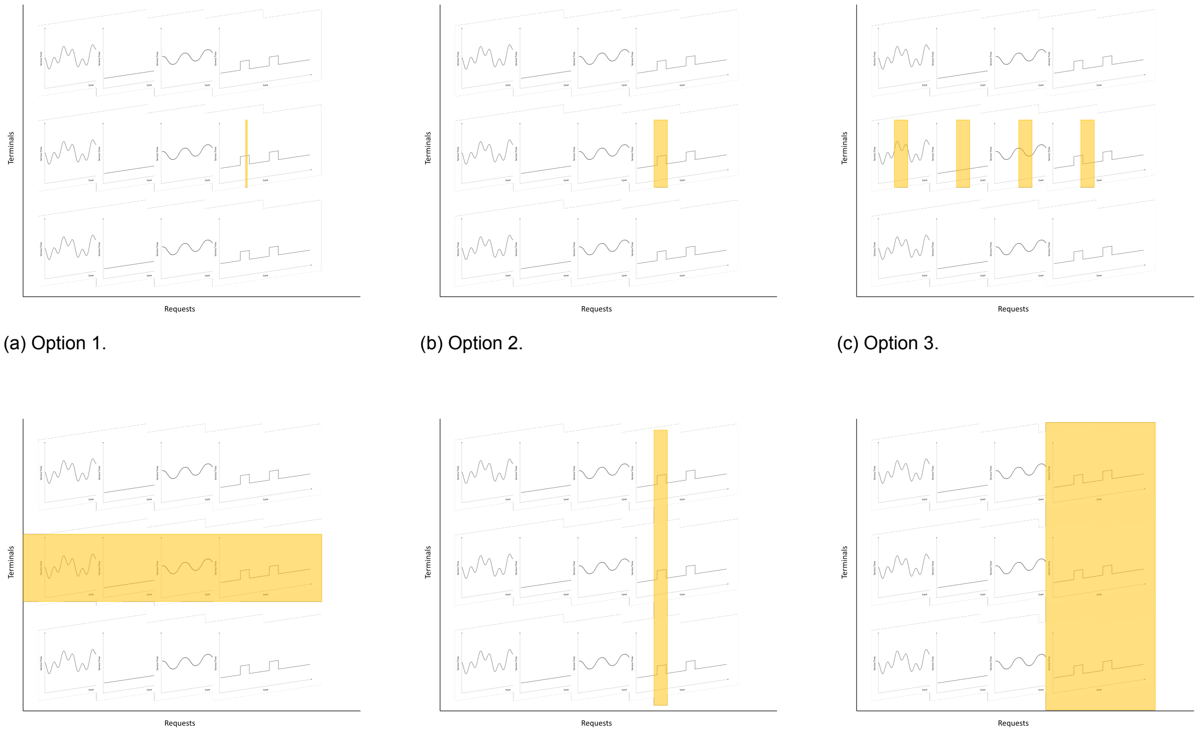


Figure 4.15: Service time matrix visualisation.

Note. Author's creation.

Another thing to discuss is what observed service times should be used to create the new estimate. Assume some iterations have been completed, and data is stored in the service time matrix. The planning agent wants to schedule pickup of request X at the Delta terminal at time 10. In this case there are a few options it could search in the service time matrix for previously observed service times for this request at this terminal at this time, so a perfect match for time, space, request and action. It could however be the case however that there are no or very limited observed service times for this specific combination of time, space and request yet. This leaves a few other options, by adding some flexibility in one of the dimensions. Regarding time, looking at the observed service times for this request at this specific terminal between a range of time, maybe between time five and fifteen. Alternatively, one could look at service times (per container) at this specific terminal at this time or also in a time range regardless of what request. If none of these options collects valuable information, the planning agent can continue with the theoretical service time. Figures 4.16 and Table 4.8 show and explain the available options that can be used to estimate the service time.



(a) Option 1. (b) Option 2. (c) Option 3.

(d) Option 4. (e) Option 5. (f) Option 6.

Figure 4.16: Service time matrix data selection options.

Note. Author's creation.

Figure 4.16a can offer the most specific data and therefore allow for a very precise estimate of the service time, if enough data is available. Figure 4.16b is also capable of giving very specific insights, although it is slightly more lenient on the time dimension, but it is still capable of providing valuable insights. Figure 4.16c is able to check the service times of multiple requests is a small time window to estimate the ”state” of a terminal - i.e. busy or not - during this time. Figure 4.16d can analyse all the service times of a terminal of all requests. In a longer timeframe this information could be very useful to update the theoretical service time at terminals. Figures 4.16e and 4.16f allow one to assess service times over multiple terminals. This could be used to gather information on what times terminals are genuinely busy. However, since terminals have a custom configuration, combining observed service times of multiple terminals will not be of much use.

Table 4.8 also shows the restrictions set on the action dimension. The service time matrix knows two types of actions being loading or unloading. The service times for these actions can differ quite a bit. Unloading practices are generally serviced quicker since they only have to be unloaded and placed in a stack. Loading actions can also involve necessary relocation movements making them more complex and potentially time-consuming. An additional aspect adding to the service time for both actions is the state of the terminal whether it is busy or not, which can cause waiting and delays. It is therefore only beneficial to base the estimated service on both type of actions if the aim is to assess the state of a terminal or multiple terminals over a small or big amount of time. For this reason only option one and two will be action based whereas the other options will be able to use findings for both action types.

Table 4.8: Service time matrix data selection options.

Figure	Dimensions				Comment
	Time - Space - Request - Action				
Figure 4.16a	Strict	Strict	Strict	Strict	*This option would only consider very specific observed service times.*
Figure 4.16b	Lenient	Strict	Strict	Strict	*This option can be used to keep the space and request dimension. It would consider space and request specific observed service times over a larger time zone.*
Figure 4.16c	Lenient	Strict	Free	Free	*If no request specific data is available, this can be used to find out if service times at this time and space are usually higher than expected.*
Figure 4.16d	Free	Strict	Free	Free	*This option can be used to find out information about the performance of a terminal over time.*
Figure 4.16e	Lenient	Free	Strict	Free	*This option can be used to find out what the service time is at a certain time without specifying the terminal.*
Figure 4.16f	Free	Free	Strict	Free	*This option is able to extract information about this specific request.*

The MAS will use a combination of options one through three, in order to get an estimate for the service time. It will first try to estimate its service time using option one, which will be used if there are at least ten observed data points available. If not available it will use option number two with a margin of one hour either side, which will increase to 5 hours either side with one hour increments until then observed data points are available. If this is also not available it will move on to option number three which will look for observed service times of other shipments at this terminal with a five hour margin either side. If this again does not return at minimum ten measurements the initial theoretical service time will be used.

The planning agent will be altered so that it can use the service time matrix to estimate its service times. In an initial situation the planning agent will create a service time matrix if that is not yet available. As soon as the service time matrix exists this matrix can be used by the terminal agents to add observed service times. These service times are already calculated and recorded in the analyse step for dwell and delay times and only have to be added to the matrix. In the next iteration the updated service time matrix can be passed to the planning agent again.

Dynamic (re)planning

The dynamic (re)planning development in the MAS is aimed to allow for scenario analysis. This development would allow to test how synchromodality would work in a network and most importantly how this will affect the container terminals. Part of the dynamic re(planning) feature is already developed simultaneously with the feedback loop and the service time matrix. This feedback loop approach already introduced the idea of having multiple iterations between the different agents in order to get more accurate estimates for the service times. The structure developed for this approach can also be used for the dynamic (re)planning.

For this functionality a few things need to be developed. Algorithm 6 shows the updated structure of the MAS with the ability to dynamically (re)planning and update the service time matrix. Compared to Algorithm 5 this new algorithm has the service matrix initialisation, updating of the service matrix after the terminal agents finished their parts. This is all part of the initial iteration.

Algorithm 7 shows the structure that is used for the complete replanning of a transport plan. In this structure the planning agent uses a dynamic planning function instead of the regular planning function.

There is not much difference between the two, apart from the fact that the dynamic planning version can use information to kick start its planning, this information consist of the service_time_matrix. The planning agent will then have to completely rebuild a transport planning using the new information available. After the PlanningAgent has completed the dynamic planning the transport plan gets reviewed by the terminal agents for several iterations.

Algorithm 6 MAS Framework - Stage 2.

Initialise planning agent
Create planning agent and generate shipment plans
Retrieve Planning Data
Extract shipment data, best routes, and route matches from the planning agent
Structure Planning Output
Process and structure data into terminal requests
Initialise terminal agents for Terminals
for each terminal **do**
    Create terminal agent with terminal requests
    Set up requests, slots, parameters, and variables
Execute MAS
for each agent in MAS **do**
    Run agent operations
Analyse Dwell and Delay Times per Vehicle
for each agent in MAS **do**
    for each action **do**
        Retrieve latest action time and planned end time
        Record dwell and delay information
Analyse Dwell and Delay Times per Request
for each agent in MAS **do**
    for each delivery action **do**
        Retrieve latest action time and planned end time
        Record dwell and delay information
        Update $service\_time\_matrix$
    for each pickup action **do**
        Retrieve latest action time and planned end time
        Record dwell and delay information
        Update $service\_time\_matrix$

The downside of doing a complete replan of the transport planning is that it can be computationally intensive, whilst a part of the transport plan might still be usable. As the number of request increases it becomes more and more attractive to only replan a part of the transport planning instead of the full transport replan, which was also proposed by Y. Zhang et al. (2022a). It described having the initial transport plan and a set of unexpected events as the input for an dynamic (re)planning algorithm. The algorithm would then identify the affected requests, re-optimise the transport plan and output the updated transport plan.

For this research a procedure is developed in slightly altered order. It will start off with identifying the affected transport requests and offer that information together with the initial transport plan to the dynamic planning function. Identifying the affected requests can be done for a couple of reasons, for example, if an action for a request is infeasible at a terminal due to too little available service time or if there is too much dwell time. However replanning this specific request can also impact the other requests that share a vehicle with this request. On the other hand for the scenario analysis what could happen is that a vehicle, link or node is affected which in term affects all the related requests. In order to get insights into how request are affected a network is made of requests, vehicles and nodes. This can be represented by a Graph as in Figures 4.17 and 4.18.

Algorithm 7 MAS framework — stage 2 (dynamic planning).

```
for i = 1 to number of iterations do
    Update planning
    Generate updated shipment plans based on current service time data
    Retrieve updated planning data
    Obtain updated shipment details, best routes, route matches, and service time information
    Execute Multi-Agent System
    for each agent in the system do
        Perform assigned agent operations
    Analyse dwell and delay times per vehicle
    for each agent in the system do
        for each vehicle action do
            Determine actual and planned completion times
            Record dwell and delay information for performance evaluation
    Analyse dwell and delay times per request
    for each agent in the system do
        for each delivery action do
            Determine actual and planned completion times
            Record dwell and delay information
            Update service time data
        for each pickup action do
            Determine actual and planned completion times
            Record dwell and delay information
            Update service time data
```

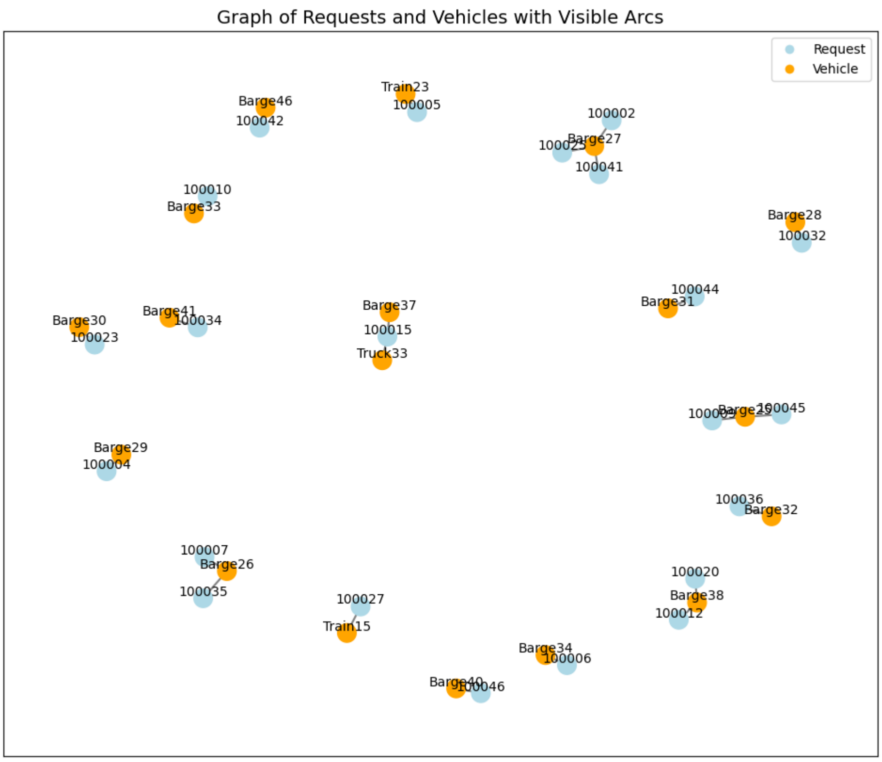


Figure 4.17: Graph of request and vehicles.

Note. Author's creation.

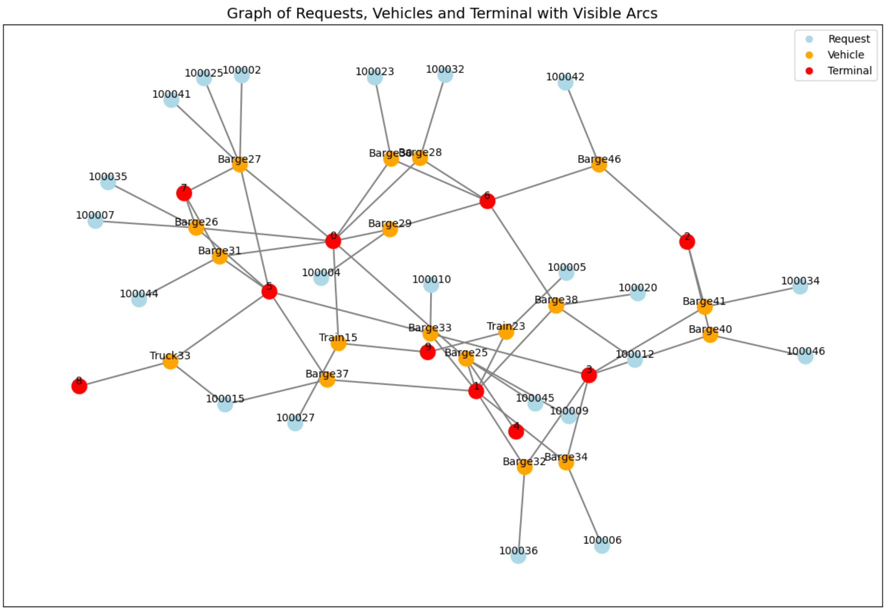


Figure 4.18: Graph of request, vehicles, and terminals.

Note. Author’s creation.

What these Figures show is that a transport planning consists can be represented by a number of clusters or one big cluster depending on what information is used to represent the network. Going back to the purpose of the network and graph representation that is to figure out how certain scenarios for replanning a single request influence other requests. Assume that request X needs to be replanned due to being infeasible to be served at a terminal. Replanning this request will impact the vehicle and the other request on this vehicle. To some degree this will also impact the terminal for which departed, transshipped and would terminate, which could potentially impact all the vehicles that use these nodes and their respective requests. However using this reasoning will cause for the full transport planning to be connected (Figure 4.18) which beats the purpose of only replanning part of the transport plan. Also the impact of replanning a single request will become less and less as you get farther away from the source. Therefore to assess the impact for replanning shipments or vehicles will only be based on a network linking requests and vehicles.

The affected requests are thus composed of the direct affected requests, for example the requests which cannot be serviced within the specified service times, and the indirectly affected requests which can be derived from the graph and its clusters. Meaning that all the requests that share a cluster with at least one of the directly affected requests are referred to as the indirectly affected requests. The set of all affected requests is passed to the dynamic planning function in the MAS together with the initial transport plan. The planning agent can then use the planning for the unaffected requests as a starting point en replan the affected requests as shown in Algorithm 8.

In case of scenarios it could be interesting to create a network to see how a single terminal affects vehicles and their request. Figure 4.19 shows how terminal five affects vehicles and requests. Such a graph could be used to identify the cluster that needs to be replanned in case a scenario would make this terminal face operational difficulties.

Also important for the scenario analysis is the time dimension. If an unexpected event happens it will only affect current or future operations. Assume that there is again a situation at terminal at time 100. If this is the case it is much more interested to see which requests are still ”active” at this time and what request are then affected by terminal five. Figure 4.20 shows how a time constraint impact the graph compared to Figure 4.19.

Algorithm 8 MAS framework — stage 2 (dynamic planning with affected requests).

Initial preparation
Retrieve initial transport plan
Retrieve set of affected requests
Retrieve current service time matrix
for $i = 1$ to number of iterations **do**
  Update planning with affected requests
  Generate updated shipment plans based on:
    — number of requests
    — service time matrix
    — initial transport plan
    — affected requests
  Retrieve updated planning data
  Retrieve updated shipment details
  Retrieve updated best routes
  Retrieve updated route matches
  Retrieve updated service time matrix

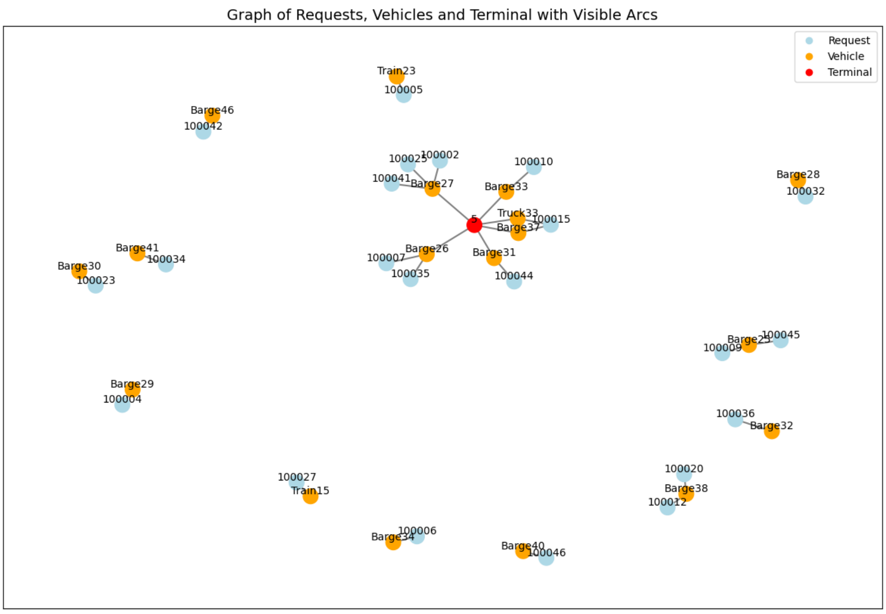


Figure 4.19: Graph of request, vehicles, and terminal 5.

Note. Author's creation.

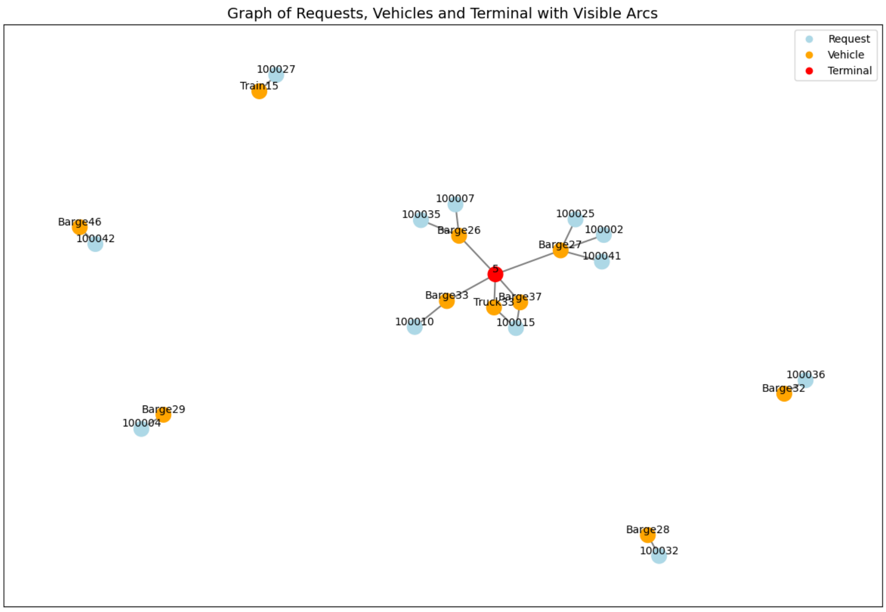


Figure 4.20: Graph of request, vehicles, and terminal 5 after time step 100.

Note. Author's creation.

4.3.3. Scenario Analysis

As stated before one of the strong suits of synchromodality is its adaptability to changing situations. With the MAS in place it would be interesting to see how this adaptability will influence container terminals and the overall integration of the stacking operations into transport planning. In order to do so this research will conduct scenario analysis. In this analysis some disruptions are proposed that will influence the execution of a transport plan and thus require dynamic replanning. For the purpose of this research two disruption types are considered, being equipment failures at ports which will temporarily cause a decrease in handling capacity, and vehicle failures, which will cancel some vehicles services unavailable from a given time onwards.

In order to facilitate this the proposed Algorithms 7 and 8 from the MAS can be utilised to explore scenario analysis in the MAS. Assuming a disruption can take place at a given time the impact that this disruption has can be taken into account for the scenario analysis. In order to properly assess how a disruption can influence the (re)planning a structure needs to be developed that so that the state of the MAS at the time of a disruption can be used as the starting point for the replanning. This concerns the time and spatial dimensions for all requests, vehicles and terminals. Algorithm 9 shows the proposed pseudo code for the scenario analysis.

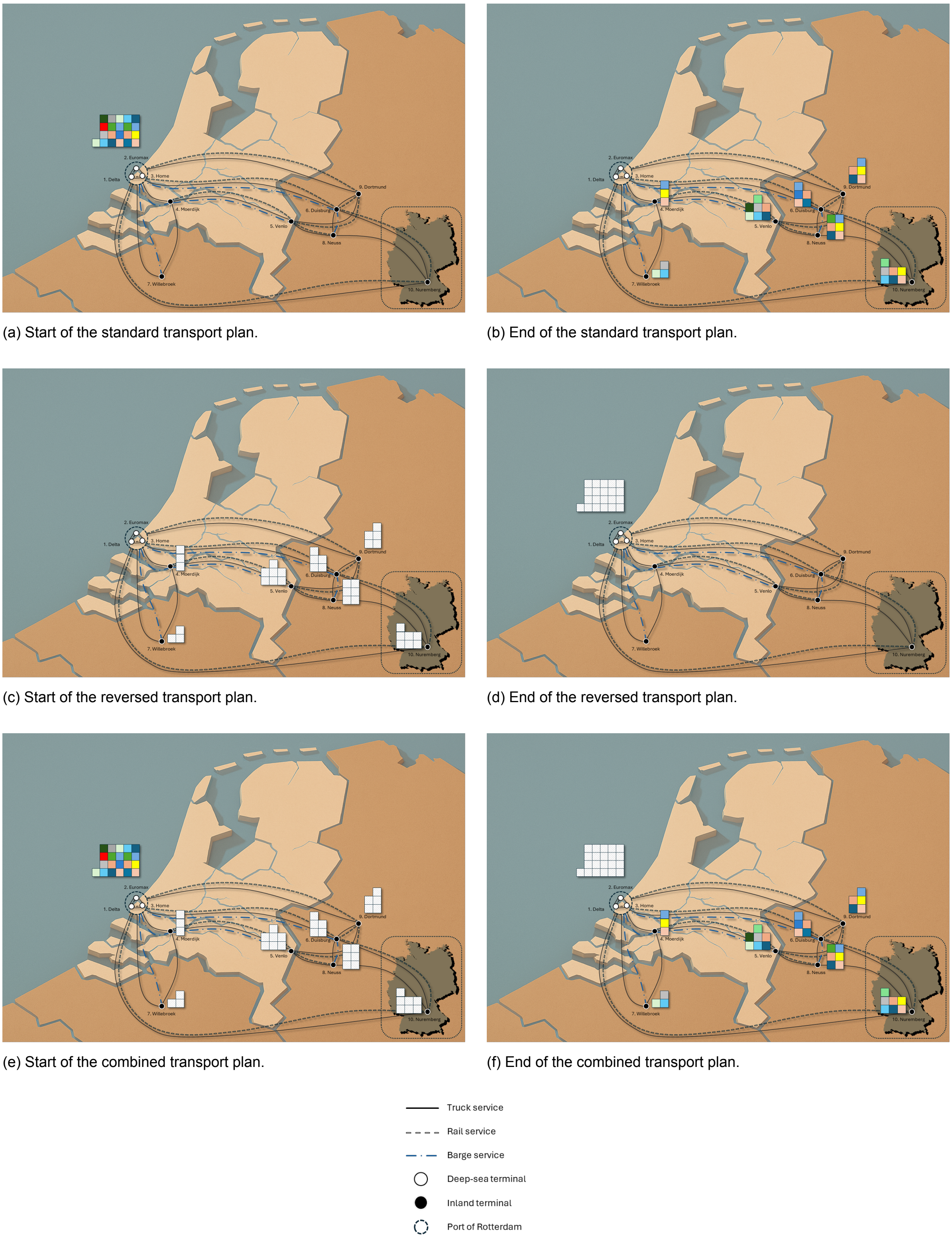
Algorithm 9 MAS framework — scenario analysis.

Define notification time
Set $t \leftarrow$ notification time
Initial planning
Execute initial planning procedure (Algorithm 6)
Execute dynamic replanning to find stable solution (Algorithm 7)
Retrieve system states
Retrieve terminal states at disruption time t
Retrieve completed requests before time t
Retrieve non-affected requests
Retrieve affected requests
Update request set
Remove completed requests from the request set
Process affected requests
for each affected request **do**
    if action has started **then**
        Move to end of current action
        Save latest terminal state
        if request delivered at end of action **then**
            Remove request from request set
        else
            Relocate request to location at end of action
            Update pickup time to end of action time
        if flexible barge involved **then**
            Relocate barge to location at end of action
            Update departure time to end of action time
Summarise actions
Summarise completed and soon-to-be-completed actions
Replan from disruption time
Execute dynamic replanning with affected requests from time t (Algorithm 8)
Combine results
Combine completed actions before t with new planning from time t

4.3.4. Reverse Flow

As introduced before, the planning agent aims at optimising a transport plan from the Rotterdam port area to its inner-city. So at the start of the planing horizon, this means that all of the containers are placed in one of the three deep sea terminals in the Port of Rotterdam, leaving all the inland terminals empty. As time moves towards the planning horizon, this will switch where the terminals in the Port of Rotterdam will be empty and the inland terminals will have all the containers in storage. In between the start and horizon of the planning, the inland containers can both store containers that have to be transshipped to another mode of transport or already store containers that terminate here.

This is of course not an ideal or realistic situation; in this case the actions of inland container terminal are for the majority placing containers in the yard that terminal there, which is not really challenging and does not induce relocations. To counter this, it is necessary to create a reverse flow from the hinterland towards Rotterdam. This could be done by adding new requests to the planning agent and giving it the additional task of planning these requests as well. This would greatly increase the computational time for the planning agent and would also require major work on all the underlying parameters. For example, expand the vehicle set and fixed service schedules in the opposite direction.



(a) Start of the standard transport plan.

(b) End of the standard transport plan.

(c) Start of the reversed transport plan.

(d) End of the reversed transport plan.

(e) Start of the combined transport plan.

(f) End of the combined transport plan.

Figure 4.21: Overview of standard, reversed, and combined transport plans, each shown at the start and end of execution.

Note. Author's creation.

An alternative option is to create a reverse flow outside of the planning agent and assume that this reversed transport plan is fixed as illustrated in Figure 4.21. This is realised as follows, since the MAS utilises an iterative approach it is possible to intercept the initial transport plan (using the theoretical service times) before it is shared with the planning agents for feedback. This initial transport plan can be copied and each task can be reversed. So for each incoming shipment for terminal A in the initial plan, the reversed transport plan will contain and outgoing shipment for terminal A. The time at which the return action will take place will will be offset by by a few hours, to avoid completely clashing with the initial transport plan. From this point on the reversed transport plan is fixed for the next iterations. Within each of the following iterations the terminal agents have to consider both the new transport plan and the reversed transport plan. Monitoring the service times for the new transport plan only, but those will indirectly be effected by the reversed transport plan as well. Based on the updated service times matrix the planning- and terminal agents have to work together to optimise the transport plan of containers into the hinterland while avoiding conflicts wit the reversed transport plan.

4.4. Conclusion on Model Development

This chapter details the technical development of the models used in this research, focusing on the STPP-FS, the SP, and the MAS that integrates them. It explains how these models are structured, modified, and integrated into a functional simulation framework.

The STPP-FS model is adapted to improve its compatibility with the SP and MAS by restructuring input and output data. One of the key modifications involves decomposing input and output components. The planning agent generates structured route data that details vehicle movements, loading and unloading operations, and transshipment activities. Additionally, to improve the realism of the planning model, the assumption of fixed parallel service times is replaced with a dynamic sequential service time approach, which determines handling times on the number of containers per request and terminal-specific handling capacity.

The SP model is adapted to more accurately represent container terminal operations in the mainland. Since the SP model traditionally focuses on pure stacking operations, it requires restructuring to align with the transport planning model. One of the primary adjustments involves converting request-based transport plans from the planning agent into a container-based structure that the SP model can process effectively. Further modifications address key limitations, including duplicate priorities, handling capacity constraints, and the inclusion of container types. The stacking model is also expanded to support multiple storage areas, each with unique handling rules. These areas include general container storage, barge gantry storage, train gantry storage, reefer storage, and empty container storage, each requiring different equipment types such as gantry cranes or reach stackers. The model also incorporates a new decision-making process for stack selection, taking into account in-yard movements. To prevent excessive repositioning of containers, a logistic decay function is introduced to penalise additional intra-terminal moves, ensuring efficient stack allocation.

The Multi-Agent System is developed in two stages. The first stage establishes passive communication, where the planning agent generates a transport plan and terminal agents evaluate its feasibility by simulating stacking operations. The terminal agents analyse vehicle dwell times and deviations in service times to assess whether the planned schedule is achievable. If a vehicle's loading or unloading takes longer than expected, the delay is recorded. Feasibility is determined by examining whether delays can be absorbed across multiple terminal visits, meaning small delays at one terminal could potentially be compensated by shorter service times at another. If the accumulated delay is too large, the transport plan is deemed infeasible.

In the second stage, active communication is introduced, allowing terminal agents to provide direct feedback to the planning agent. To support this, a Service Time Matrix (STM) is developed, which stores observed service times across different terminals, time slots, and request types. This matrix enables the system to adjust planning dynamically, using recorded data to refine service time estimates. The MAS operates iteratively, updating the transport plan over multiple runs to gradually improve its accuracy. Instead of assuming fixed handling times, the system learns from previous iterations by analysing patterns in service times and congestion levels. This approach is inspired by demand forecasting techniques used in logistics, where historical data is leveraged to optimise resource allocation.

Dynamic replanning is a key feature of the MAS, allowing for scenario analysis and adaptation to unexpected events. The system can identify affected requests and vehicles in response to disruptions such as terminal congestion or equipment failures. Using a graph-based approach, the MAS determines which parts of the transport network are impacted and selectively replans affected shipments while preserving feasible sections of the original transport plan. This ensures that the system remains flexible and can adjust to operational changes efficiently.

5

Results and Analysis

The purpose of this chapter is to evaluate the performance of the proposed framework by analysing three key aspects: (1) the computational impact of modifications to the Stacking Problem, (2) the integration of the adapted stacking model within the Synchromodal Transport Planning Problem with Flexible Services in the MAS, and (3) the system's response to various disruption scenarios. By conducting these analyses, the chapter provides insights into the trade-offs between computational efficiency, enhanced decision-making, and system adaptability.

5.1. Computational Impact of Adapted Stacking Problem

The first evaluation focuses on quantifying the computational impact of modifications made to the original SP heuristic. Since direct one-to-one comparisons are not feasible due to additional features and changes in setup, the analysis focuses on the increase in computational complexity and trade-offs in efficiency over a broader landscape.

5.1.1. Experimental Setup

A set of test instances is defined to compare the execution times and the usage of computational resources of the original and adapted SP models. These instances are categorised on the basis of problem size, stacking constraints, and operational conditions. In the original paper Expósito-Izquierdo et al. (2015) conducted a computational comparison of their proposed models against models proposed in other papers. Under varying settings, different amounts of stacks, stack height, and numbers of containers, the proposed model was able to outperform other models.

The original and adapted SP are tested under different circumstances with comparable configurations in terms of available stacks, tiers, and containers. The containers are generated to have random arrival and departure times; the time they spend within the stack can be controlled so that the average occupancy rate in a stack can be set. As an example, setting the occupancy rate at 0.6, with 100 containers, 400 time steps, and 100 available capacity, means that each container will spend, on average, 240 time steps in the yard, calculated according to Equation 5.1. Each configuration is tested using the occupancy ratios of 0.5 and 0.8. Each combination is repeated at least five times, each with new randomly assigned container arrival and departure times.

$$\text{Average Time in Terminal} = \frac{\text{Horizon Time}}{\left(\frac{Containers}{Capacity \cdot Occupancy}\right)} \tag{5.1}$$

5.1.2. Performance Metrics

The metric used for relocations is expressed as the number of relocations relative to the number of containers. The increase in the number of relocations is also expected. The adapted SP has less flexibility for the same overall capacity than the original SP. Since the adapted version has numerous yards with their own restrictions, the different containers cannot compensate for one another. In the original version there is a single stack that stores all containers, regardless of type. In the adapted version there are multiple stacks, like one for normal containers and one for reefer containers. Assume a set of normal containers arrives with a late departure time; after that, reefer containers arrive with an early departure time, and after that, another set of reefer containers arrives with a later departure time. In the original model, the normal containers can be placed at the bottom, and then the early departure reefer containers can be stacked efficiently on top of this, leaving space for the late departure reefer containers. In the adapted version, the normal containers are stored in the big stack, but the reefers have to be stored in a special reefer stack with low capacity. Placing the early departure reefer containers first will then block them from being retrieved later.

5.1.3. Results

Figure 5.1 shows the comparison of the observed computational time and relocation performance for each batch of containers. What this figure shows is that the computational time increases as the capacity (stacks × tiers) increases. This is explained by the fact that the number of containers used for each instance is based on the number of tiers and stacks for each configuration. For the adapted SP compared to the original SP, these figures also show an increase.

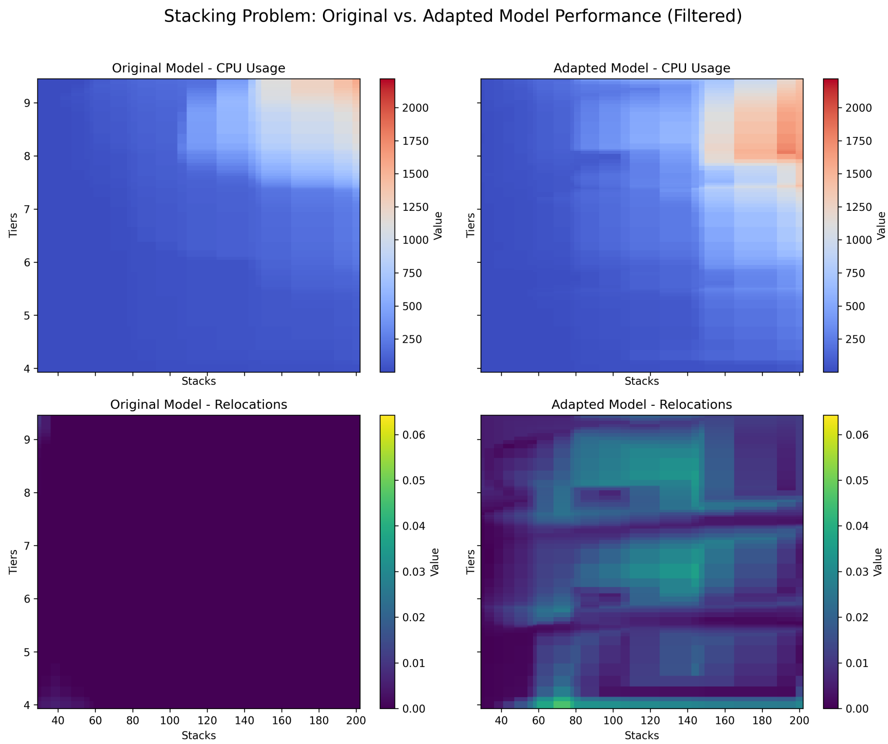


Figure 5.1: Heat map of performance indicators for original vs. adapted stacking problem.

Note. Author’s creation.

Given that the adapted SP models multiple storage areas and considers inbound and outbound characteristics, these computational increases are still substantial but within an acceptable range for this study. The experimental setup also considered that each container arrives and departs in the terminal, meaning two actions per container. In the MAS, containers only depart from their original terminal and terminate at their final terminal. At a transshipment terminal, the containers do have an arrival and departure, thus two actions; however, not every container has a transshipment. The next section discusses the integration of the SP and STPP-FS in the MAS, where the computational performances will be further discussed.

5.2. Evaluation of Integrated Multi-Agent System

This section evaluates the impact of replacing passive terminal nodes in STPP-FS with active agents that incorporate the adapted Stacking Problem model. The analysis focuses on system performance, coordination complexity, and decision-making improvements.

5.2.1. Experimental Setup

In order to evaluate the MAS, a baseline needs to be established; this will be the slightly adapted STPP-FS in this paper. These adaptations are limited to the implementation of sequential service times and theoretical service times provided via the service time matrix. Each one of these configurations will be tested under conditions with flexible trucks in one instance and flexible barges and trucks in the other. The computational performance as well as the objective value are recorded for all request sets ranging from five to 200 requests. Y. Zhang et al. (2022a) reported computational times of up to three hours to solve this instance when considering both flexible trucks and barges, whereas the computational time for 400 requests goes up to nearly 9 hours. Given that the planning has to be replanned over a couple of iterations in order to build the service-time matrix, this becomes unworkable. Added to this, Table 3.10 shows that the number of containers also increases from 4,000 to over 8,000 between 200 and 400 requests, making computational times for the SPs also very challenging.

The next step is to compare the performance of the MAS against the STPP-FS. This will take into account the objective performance as well as the computational performance. After the initial planning, there are ten feedback loops to build up the service time matrix. Compared to the testing of the plan STPP-FS, the planning agent in the MAS will also be set to plan all available requests that are available. The STPP-FS algorithm will have 200 iterations to optimise its planning; the MAS will have its 200 ALNS iterations distributed over the ten iterative stages used in the MAS to allow for feedback between the agents.

5.2.2. Performance Metrics

Key performance metrics for the STPP-FS include the computation time and overall costs. Key performance metrics for the terminal agent consist of the total number of actions at a terminal and total relocations. Key performance metrics for the full MAS are focused on dwell times of vehicles at the terminals and the ratio of actions that can be served within the specified window. The results help quantify the added complexity and benefits of agent-based decision-making.

In assessing the MAS, each request set has been subjected to an initial planning followed by ten iterations of assessing the transport plan by the terminal agents and replanning the requests. With each iteration, the goal would be to maximise the number of requests that are planned by the planning agent, maximise the number of actions that can be served by the terminal agents, and minimise the dwell time of vehicles at the terminals. The recorded metrics are planning CPU time, planning success rate (i.e., the portion of requests that are planned), overall planning cost, terminal CPU time, total terminal actions, served terminal actions, terminal dwell time per served action, and the total terminal relocations. The planning agent will provide transport planning to the terminal agents who will assess this. If an action at one of the terminals is infeasible or has a dwell time exceeding fifteen minutes, this will be passed back to the planning agent for replanning in the next iteration. An action with excessive dwell time will still count towards a 'served' question.

5.2.3. Results

The results of the MAS evaluation are divided into three subparagraphs. The first paragraph is set out to focus on how the MAS performs against the STPP-FS in terms of CPU performance and the main objective. The second paragraph will analyse the MAS performance and behaviour from the planning perspective, discussing how the planning success and planning cost objective change between iterations. The third paragraph will have the same approach now, focusing on the terminal perspective. And the final paragraph will discuss the overall performance and behaviour of the MAS, focusing on the integration performance of the planning agent and terminal agent.

Mas Performance vs. STPP-FS

Starting with the cost baseline metrics for the STPP-FS in Figure 5.2. This graph shows reference lines from records from Y. Zhang et al. (2022a). L_1 describes the objective value obtained considering flexible route planning for trucks and L_2 shows the obtained objective value considering flexible planning for both barges and trucks. This shows that the results between the original STPP-FS and the MAS are fairly similar for the smaller request sets, but for request set 200 the obtained objectives are considerably worse. There could be a number of reasons for this difference in the obtained objective values. For example, the fact that the machine on which these experiments are run has less computational power and is therefore less likely to find the optimal solution. Another possible explanation is that it could be the result of the implementation of sequential loading instead of parallel loading. This could make it a lot more complex to load multiple requests on the same transport leg.

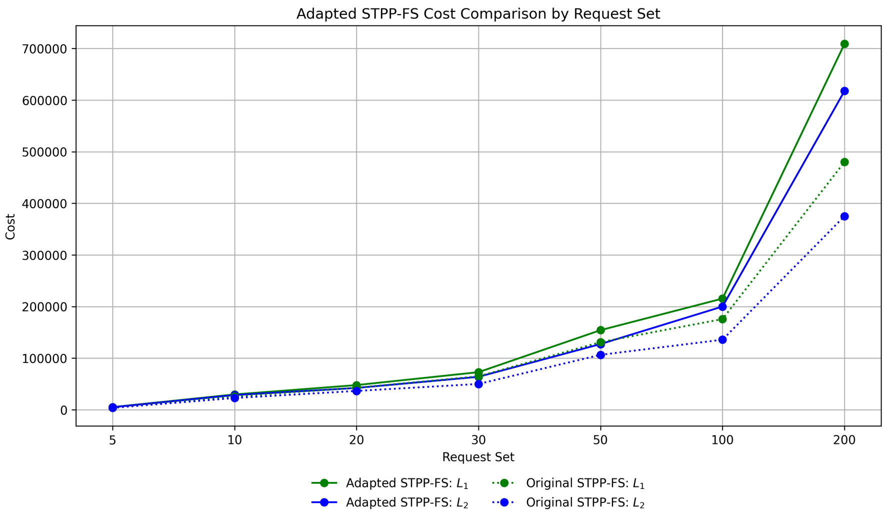
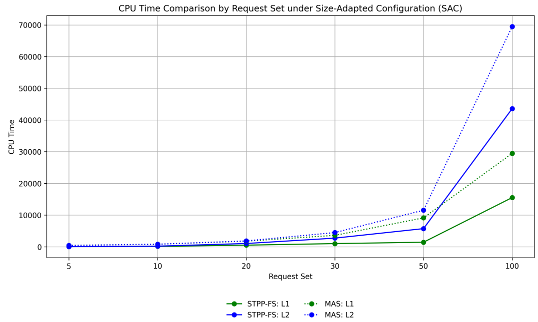


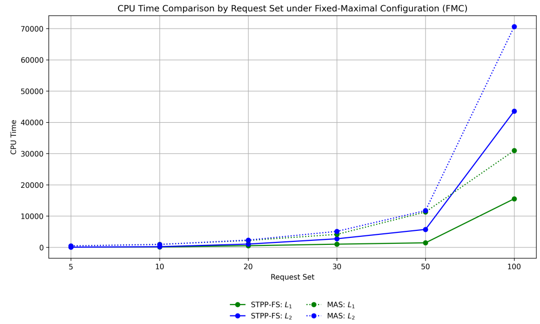
Figure 5.2: Adapted STPP-FS cost comparison by request set.

Note. Author's creation. L_1: Flexible Trucks, Fixed Barges and Trains. L_2: Flexible Barges and Trucks, Fixed Trains.

The graphs in Figure 5.3 show the computational performance of the MAS and the adapted SP for each request set under both SAC and FMC. This shows a near-exponential increase in computational time as the set of requests increases. Looking at the computational time for the MAS at the L_2 setting, this approaches 20 hours of running time for SAC. On average the computational time of the MAS is over 50% greater than that of the STPP-FS for the same request set. Since the observed computational time of the MAS is substantially higher and increases exponentially, together with the fact that Figure 5.2 indicated that adapted STPP-FS is more out of touch with the original setup as the request size increases, request set 200 will not be considered further.



(a) Size-Adapted Configuration (SAC).

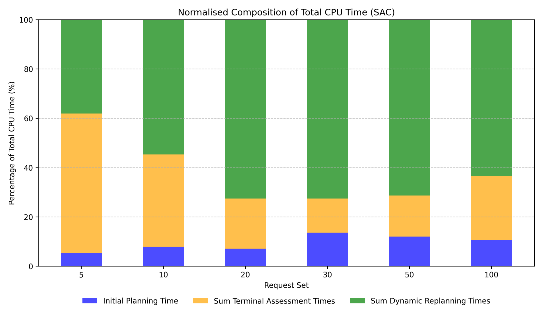


(b) Fixed-Maximal Configuration (FMC).

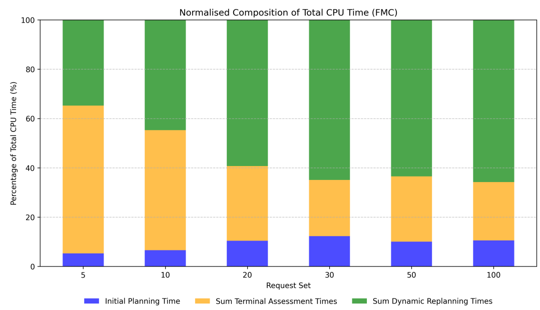
Figure 5.3: Graph of CPU time performance for STPP-FS vs. multi-agent system.

Note. Author's creation. L_1: Flexible Trucks, Fixed Barges and Trains. L_2: Flexible Barges and Trucks, Fixed Trains.

Figure 5.4 shows how the computational time of the MAS is distributed between the different stages. This shows the percentage of time that is spent on the initial planning, terminal assessment times (initial assessment plus ten improvement assessments), and dynamic replanning times. On average, five to ten per cent of the total time is spent on the initial transport planning under both SAC and FMC conditions. Under SAC conditions with smaller terminal configurations, it shows that the overall time spent on terminal assessment is lower than that compared with under FMC conditions. What is also interesting is that the portion of time spent on the container terminal assessment is first relatively high, then drops off and seems to increase again at the end. As shown in Table 3.10, there is a consistent increase in containers related to the increase in requests. On average, for each request there are twenty containers. From the perspective of a Stacking Problem, the total number of containers is more relevant for the performance than the number of requests.



(a) Size-Adapted Configuration (SAC).



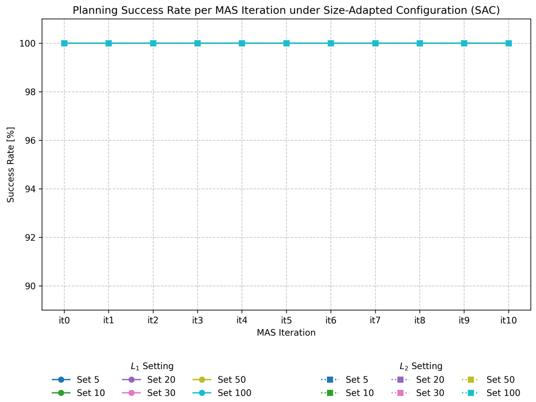
(b) Fixed-Maximal Configuration (FMC).

Figure 5.4: Graph of normalised composition of total multi-agent system CPU time.

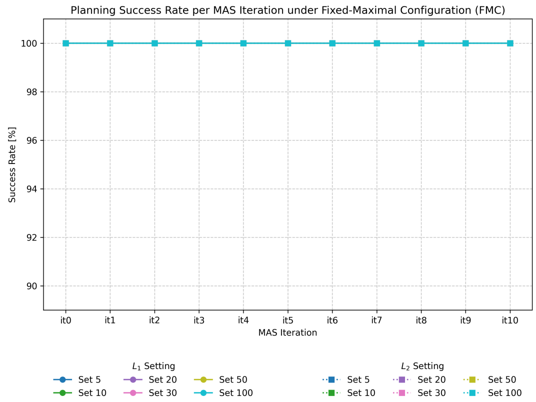
Note. Author's creation.

MAS Planning Performance

The planning performance will be assessed by analysing two metrics. The first of those metrics is shown in Figure 5.5, which illustrates the success rate of the planning per MAS iterations. The success rate of planning is expressed as the portion of requests that are included in the planning compared to the total number of available requests. The planning agent is not always able to directly plan all of the requests and therefore needs a couple of ALNS iterations to do so. The graphs in Figure 5.5 show that the planning agent in the MAS is able to plan all of the available requests even though the ALNS iterations are divided on the MAS iterations.



(a) Size-Adapted Configuration (SAC).



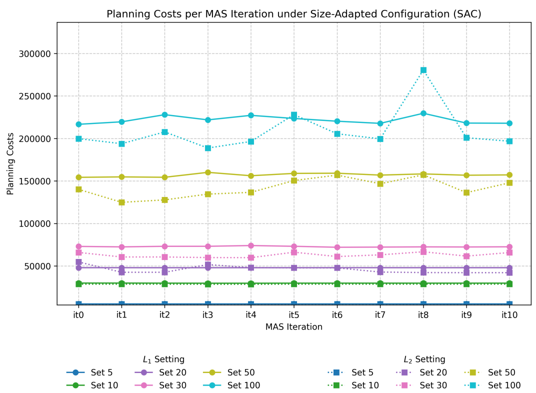
(b) Fixed-Maximal Configuration (FMC).

Figure 5.5: Graph of planning success rate per MAS iteration.

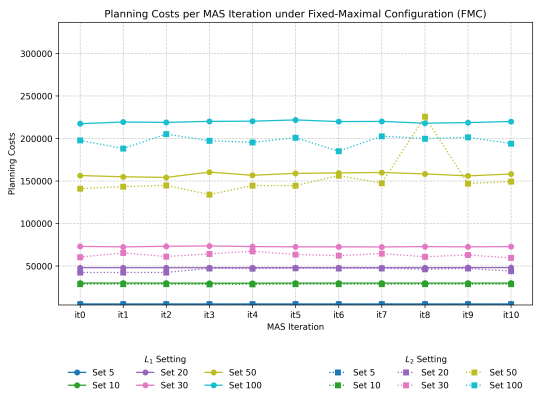
Note. Author's creation.

The second metric to discuss is how the overall planning objective and the total planning costs develop over time; this is shown in Figure 5.6. With the introduction of the feedback loop between the terminal and planning agent, it is expected to improve the overall feasibility of the planning and terminal operations, but at what cost? What generally can be observed between Figures 5.6a and 5.6b is the overall cost objective is fairly similar between the MAS under SAC and FMC. So from a planning perspective, the overall or extra capacity of a terminal does not have too much influence on the planning objective, at least not in the larger picture. Looking at the progression of the planning objective over the MAS iterations, it is seemingly stable with some peaks and troughs, mostly under the L_2 setting.

A potential cause of this more erratic behaviour under the L_2 setting is that due to the added flexibility, more of the spatial and time dimensions can be explored in the planning phase. This would therefore require more observations in the STM before a stable output of service times can be estimated. In general, it can be stated that the integration of synchromodal planning and terminal operations does not have a negative effect on the overall planning performance.



(a) Size-Adapted Configuration (SAC).



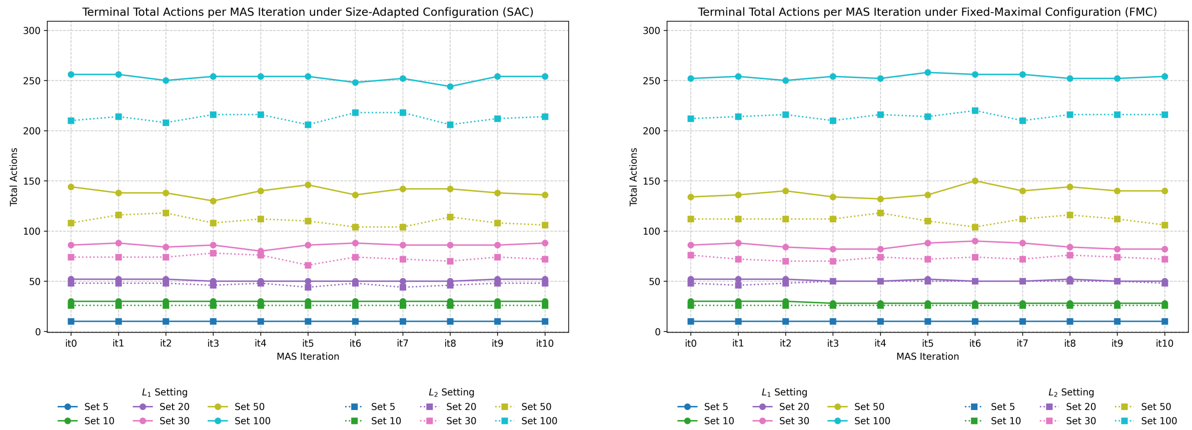
(b) Fixed-Maximal Configuration (FMC).

Figure 5.6: Graph of planning cost objective per MAS iteration.

Note. Author's creation.

MAS Terminal Performance

Similarly to assessing how the integration of planning and container stacking influences the planning objectives, this paragraph focuses on the influence it has on the terminal performance. In order to do so, this paragraph will discuss two key metrics: these are the total number of actions at the terminals and the total number of relocations at the terminals. Starting with the total number of actions at the terminals, illustrated in the graphs in Figure 5.7. The total number of actions is determined as the sum of all loading and unloading actions on all terminals. Comparing Figures 5.7a and,5.7b they show very similar results, indicating that neither the size of the terminals nor the integration of planning and container stacking has much influence on the total number of actions at the terminals.



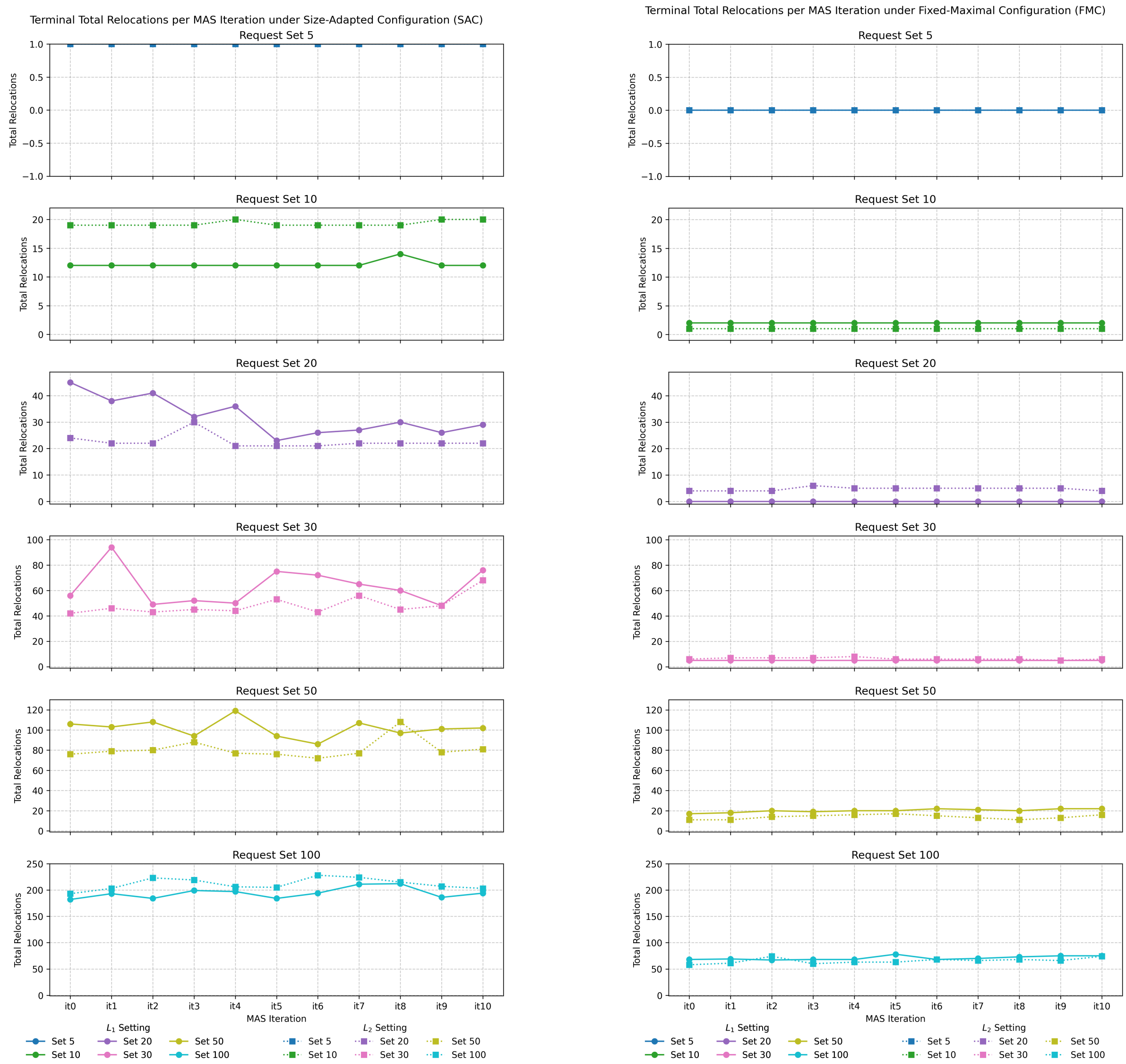
(a) Size-Adapted Configuration (SAC).

(b) Fixed-Maximal Configuration (FMC).

Figure 5.7: Graph of terminal total actions per MAS iteration.

Note. Author's creation.

Figure 5.8 shows the graphs for the number of relocations, and this shows a lot more variance. Comparing the results under SAC and FMC shows very different results. This is as expected since a terminal with a lot more available slots should experience a lot fewer relocations. Under SAC, Figure 5.8a, the average number of relocations is thus a lot higher. Looking at the progression over the MAS iterations, it shows again a fairly erratic behaviour. This indicates that in between each iteration and as more and more feedback is gathered, there are definitely some shipments moving around. This is sometimes expressed as a decline in relocations, for example, with request set 20 under SAC, but most of the time it stabilises around the initial observed number of relocations.



(a) Size-Adapted Configuration (SAC).

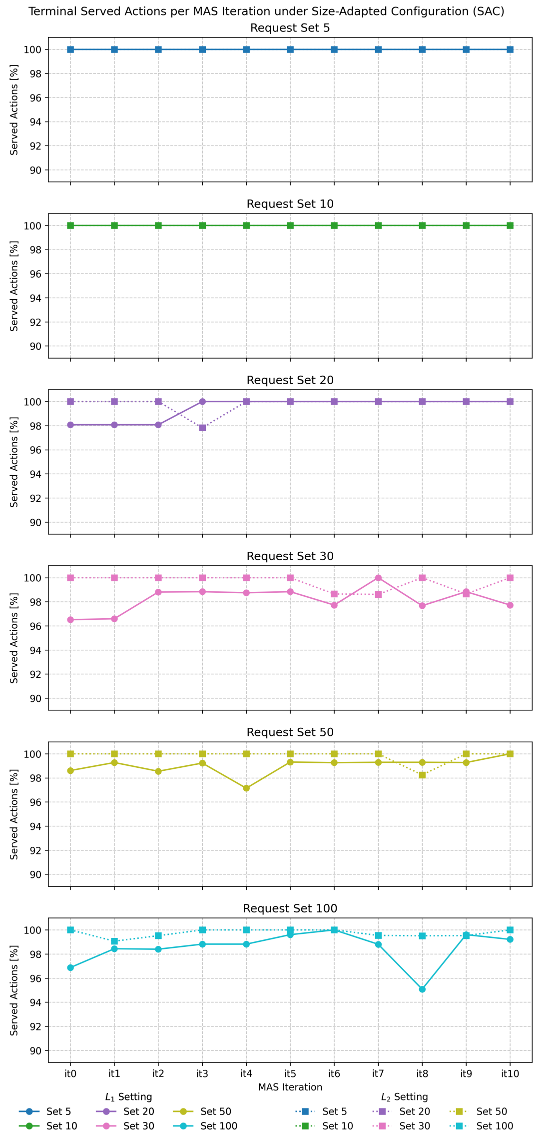
(b) Fixed-Maximal Configuration (FMC).

Figure 5.8: Graph of terminal total actions per MAS iteration.

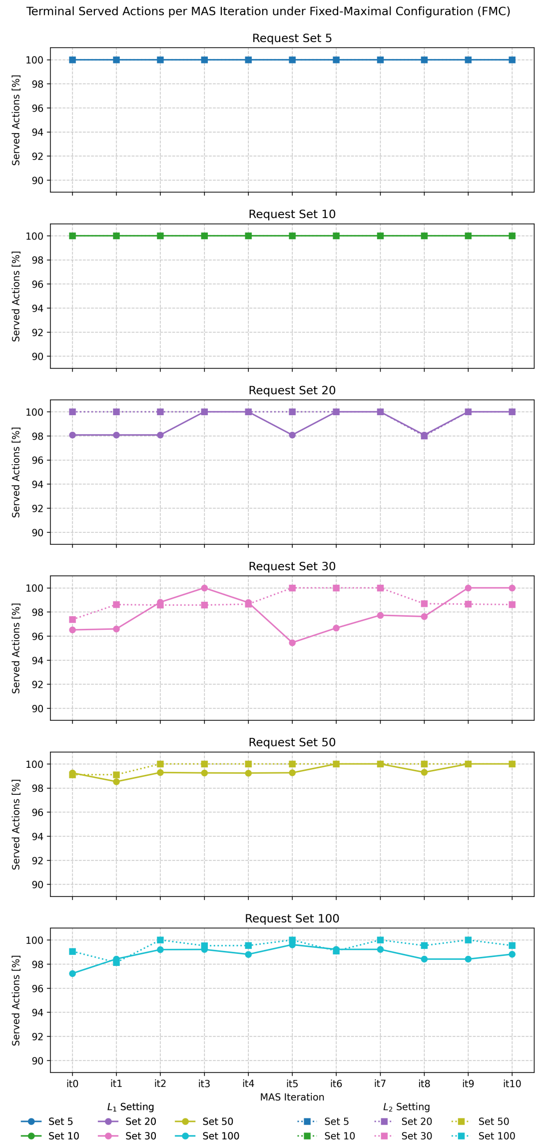
Note. Author's creation.

MAS Integration Performance

The last paragraph discussing the evaluation of the MAS is focused on the integration performance of the planning and terminal agent. The two metrics discussed for this focus on the progression of the average dwell time and, most importantly, the portion of served actions at terminals. Figure 5.9 shows the portion of served actions, which is expressed as the total number of actions at terminals that can be executed by the terminals within the given time window compared to the total number of actions at the terminals. These graphs show a general improvement throughout the iterations towards an eventual feasible plan. This is due to the service time matrix and feedback from the terminals taking effect. It still shows some instability in the later iterations, sometimes moving away from a perfectly feasible plan, but it is a very positive result that for each request set under both L_1 and L_2 settings as well as under SAC and FMC, a feasible plan can be achieved within ten improvement MAS iterations.



(a) Size-Adapted Configuration (SAC).

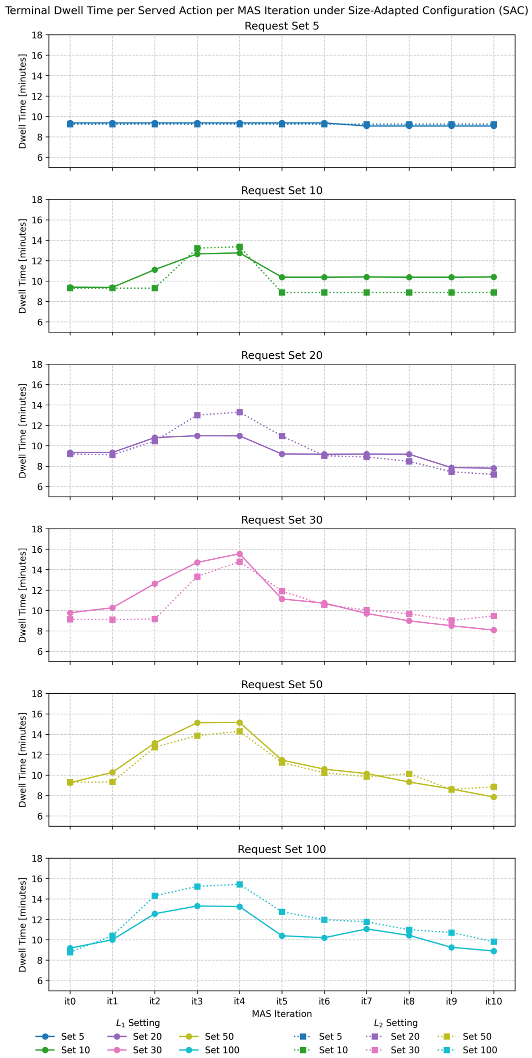


(b) Fixed-Maximal Configuration (FMC).

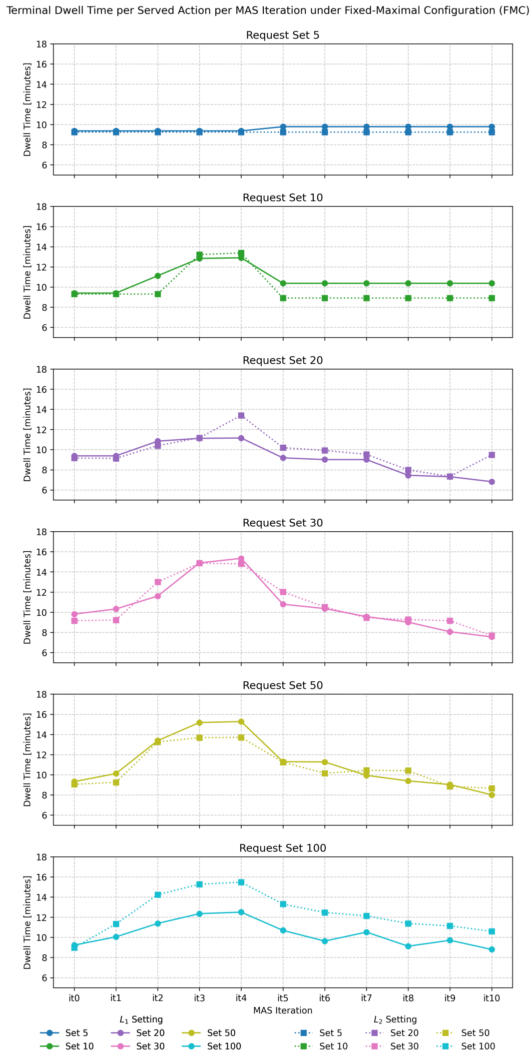
Figure 5.9: Graph of portion of served actions at terminals per MAS iteration.

Note. Author's creation.

The second metric to discuss is the average dwell time per served action. Figure 5.9 showed positive results in the fact that the terminals were able to serve more actions as more feedback was given. It is, however, also important to monitor the dwell time at terminals. A plan can be feasible, but if large dwell times are observed, it is not good planning. Figure 5.10 shows the graphs for the average observed dwell time per action for each MAS iteration. Across all settings and configurations, the same behaviour is observed, that is, an initial increase in dwell time throughout the first 5 iterations and then a steady decline in the last five iterations. This is probably a result of the applied standard deviation in the estimated service times; in the beginning, these standard deviations are probably quite big, causing higher service time estimates. As the number of observed service times increases, this estimate gets better and better, and even further, the average dwell time approaches a value similar to that of the initial MAS iteration or even lower.



(a) Size-Adapted Configuration (SAC).



(b) Fixed-Maximal Configuration (FMC).

Figure 5.10: Graph of terminal dwell time per MAS iteration.

Note. Author's creation.

5.3. Scenario Analysis: System Response to Disruptions

This section evaluates the system's response to real-world uncertainties by simulating disruptions in container transportation. One of the key strengths of synchromodality lies in its ability to swiftly adapt to changing conditions, ensuring resilience and efficiency in logistics operations. To assess this adaptability, various disruption scenarios are introduced, such as delays in barge and rail services and equipment failures. The system's reaction to these challenges is analysed by examining shifts in modal choices, rescheduling strategies, and the overall impact on container flows. By simulating such disruptions, the analysis provides insight into the robustness of synchromodal transport planning and its effectiveness in mitigating operational risks.

5.3.1. Experimental Setup

For the scenario analysis, two types of disruptions are considered. The first one is an equipment failure at the Delta terminal, which is the biggest terminal in the network, resulting in decreased terminal throughput and longer handling times. The second is vehicle failures, in which case a random selection of vehicle services from the original transport plan is made unavailable.

In the experimental setup, multiple variations of these disruptions are tested with request set 30, consisting of nearly 1,300 containers. Note that this includes the reverse flow containers as introduced in Section 4.3.4. Each disruption is associated with a notification time or notification delay, which indicates how long it takes before the planning agent becomes aware of the disruption. By varying the time between the occurrence of a disruption and its notification, the analysis assesses the impact of synchromodal planning on disruption recovery and its broader effects on container terminal performance. While this approach does not strictly replicate a fully synchromodal mode of operation compared to a multimodal one, it enables an evaluation of different degrees of vertical and horizontal integration within synchromodality. This, in turn, provides insights into the flexibility and resilience of the system under varying levels of integration and responsiveness. Table 5.1 shows an overview of the used disruption types. Each of these fifteen disruption configurations is repeated 5 times under both SAC and FMC.

Table 5.1: Scenario disruptions

Disruption Type	**Disruption Effect**	**Time From** [h]	**Duration** [h]	**Notification Delay** [h]
Equipment Failure A	Handling Capacity at 70%	[48-72]	48	+0
Equipment Failure A	Handling Capacity at 70%	[48-72]	48	+4
Equipment Failure A	Handling Capacity at 70%	[48-72]	48	+8
Equipment Failure B	Handling Capacity at 30%	[48-72]	48	+0
Equipment Failure B	Handling Capacity at 30%	[48-72]	48	+4
Equipment Failure B	Handling Capacity at 30%	[48-72]	48	+8
Vehicle Failure A	One service cancelled	[48-72]	∞	+0
Vehicle Failure A	One service cancelled	[48-72]	∞	+4
Vehicle Failure A	One service cancelled	[48-72]	∞	+8
Vehicle Failure B	Five services cancelled	[48-72]	∞	+0
Vehicle Failure B	Five services cancelled	[48-72]	∞	+4
Vehicle Failure B	Five services cancelled	[48-72]	∞	+8
Vehicle Failure C	Ten services cancelled	[48-72]	∞	+0
Vehicle Failure C	Ten services cancelled	[48-72]	∞	+4
Vehicle Failure C	Ten services cancelled	[48-72]	∞	+8

Note: Time From gives a time range from which a time can be randomly drawn.

5.3.2. Performance Metrics

The response of the planning and terminal agents to these disruptions is analysed based on system resilience, reallocation of resources, and adaptability of scheduling decisions. Specifically, the observed metrics are the costs in the planning objective and overall performance at the terminals, which will be expressed by the number of relocations. An additional metric is used, which is the change in modal split from original planning to the disruption-adapted planning. The modal split is calculated based on transport legs and the size of the requests.

5.3.3. Results

Tables D.1 through D.10 in Appendix D present the raw data on both the absolute and percentage (or percentage point) differences in the observed results between the initial transport plan and the disruption-adapted transport plan. The initial scenario analysis consists of 150 tests, with the first 75 tests conducted with terminals under size-adapted configuration and the second 75 with terminals under fixed-maximal configuration. The summarised results are shown in Tables 5.2 and 5.3. These tables show the average absolute change and percentage change between the initial and disruption-adapted transport plans. In addition, a p-value is presented, which indicates whether the differences between the observed values for the disruption-adapted plan and the original plan are statistically significant. A paired, two-tailed t-test was used to assess whether the observed values for the disruption-adapted plan differed significantly from those in the original plan.

Table 5.2: Scenario analysis: planning agent cost objective.

Disruption		**Planning Agent**							
Type	n	Overall	Request	Wait	Trans-shipment	(Un)loading	Emission	Storage	Delay
SAC	75	8098.95 11.1% p<0.001	5784.93 15.4% p<0.001	-2.01 -12.0% p<0.001	-1554.88 -20.2% p<0.001	-1129.36 -5.2% p<0.001	25.64 5.3% p<0.001	174.13 3.9% p=0.014	4800.51 428.6% p<0.001
FMC	75	6833.72 9.4% p=0.002	4605.78 12.3% p=0.003	-1.81 -10.8% p<0.001	-1436.83 -18.7% p<0.001	-1202.72 -5.5% p<0.001	34.17 7.0% p<0.001	201.80 4.5% p=0.005	4633.32 413.7% p<0.001

Note. pp = percentage points; p = p-value (two-tailed t-tests).

Table 5.3: Scenario analysis: terminal agent objectives and modal shift.

Disruption		**Terminal Agent**		**Modal Split**		
Type	n	Reshuffles	Transshipments	Barge	Train	Truck
SAC	75	-32.95 -1.5% p=0.006	-40.99 -17.3% p<0.001	-5.63pp -13.3% p<0.001	3.15pp 15.9% p<0.001	2.48pp 6.6% p<0.001
FMC	75	1.60 4.3% p=0.022	-31.09 -13.0% p<0.001	-4.85pp -11.2% p<0.001	2.43pp 13.3% p<0.001	2.42pp 6.3% p<0.001

Note. pp = percentage points; p = p-value (two-tailed t-tests).

The results from Tables 5.2 and 5.3 show some interesting results. From the planning perspective, it shows a significant cost increase of around ten per cent in the disruption-adapted plan, which is expected as the disruptions cause suboptimal conditions. Further cost analysis shows significant increases in request, emission, and delay costs, while the transshipment and (un)loading costs experience a significant decrease. These are all early indications of less multi-modal transport and a modal shift. This is confirmed by assessing the metrics from the perspective of the terminal agent and the modal shift. These show significant decreases in the number of transshipments and significant modal shifts from barges towards the faster and more expensive train mode and the faster, more expensive, and more flexible truck mode. The number of reshuffles also shows a significant and substantial decrease under SAC, while under FMC the results show a slight significant increase. This all adds up: the increase in request costs is a result of the more expensive modes; transshipment costs are lower due to fewer transshipments; (un)loading costs are down due to lower handling costs for trucks; emission costs are up due to the modal shift; and finally, the increase in delay costs can be attributed to the disruption itself.

Intuitively, these results make a lot of sense, as these disruptions occur, the planner has less flexibility, and in order to optimise the planning, it has to utilise the faster and flexible modes, even when it increases the overall costs. To further test these results and the hypothesis that these results are reasonable, three additional scenario conditions are tested. These scenario conditions are designed to give the planning agent slightly more flexibility in making the disruption-adapted plan. In the first two scenario conditions the exact same scenarios from Table 5.1 are repeated, but this time the penalty for delays is decreased by 10% and 50%. The third scenario condition is where the delivery window is extended by 24 hours. The idea here is that given a disruption, there is some sort of force majeure situation in which the customers are more lenient towards a delay in the delivery of their goods. This should, in turn, allow the planning agent to use more of the slower transport modes and be less dependent on the flexible, high-polluting trucks.

Table 5.4: Scenario analysis: planning agent cost objective under force majeure conditions.

Disruption		**Planning Agent**							
Type	n	Overall	Request	Wait	Trans-shipment	(Un)loading	Emission	Storage	Delay
Penalty - 10%	75	3014.28 4.1% p=0.152	-368.59 -1.0% p=0.904	-2.17 -13.0% p<0.001	-1425.12 -18.5% p<0.001	-1565.39 -7.2% p<0.001	35.83 7.3% p<0.001	211.54 4.7% p=0.006	6128.18 547.2% p=0.011
Penalty - 50%	75	-529.72 -0.7% p=0.892	-1083.04 -2.9% p=0.844	-2.28 -13.6% p<0.001	-1419.47 -18.4% p<0.001	-1740.37 -8.0% p<0.001	33.67 6.9% p<0.001	87.40 2.0% p=0.252	3594.37 320.9% p=0.053
Window + 24h	75	-4715.98 -6.5% p=0.056	-1122.59 -3.0% p=0.635	-2.19 -13.1% p<0.001	-1337.33 -17.4% p<0.001	-1508.53 -6.9% p<0.001	28.57 5.9% p<0.001	238.41 5.3% p=0.009	-1012.32 -90.4% p<0.001

Note. pp = percentage points; p = p-value (two-tailed t-tests).

Table 5.5: Scenario analysis: terminal agent objectives and modal shift under force majeure conditions.

Disruption		**Terminal Agent**		**Modal Split**		
Type	n	Reshuffles	Transshipments	Barge	Train	Truck
Penalty - 10%	75	-61.12 -3.1% p<0.001	-14.92 -6.3% p<0.001	-5.35pp -12.6% p<0.001	1.29pp 6.5% p=0.006	4.07pp 10.8% p<0.001
Penalty - 50%	75	-32.41 -1.6% p=0.031	-17.92 -7.5% p<0.001	-6.01pp -14.2% p<0.001	1.39pp 7.0% p<0.001	4.62pp 12.2% p<0.001
Window + 24h	75	-38.63 -2.0% p=0.001	-14.47 -6.1% p<0.001	-4.73pp -11.2% p<0.001	1.03pp 5.2% p=0.013	3.70pp 9.8% p<0.001

Note. pp = percentage points; p = p-value (two-tailed t-tests).

The results from the tests under the force majeure conditions are shown in Tables 5.4 and 5.5. The scenario tests under these conditions yield slightly unexpected results. The hypothesis was that more leniency in the delay penalty would result in less of a modal shift towards the more polluting modes. The opposite is seemingly true, with an even more extreme significant modal shift taking place towards specifically the truck usage of around four percentage points compared to roughly 2.5 in Table 5.3.

There are, however, also other interesting changes. Table 5.2 showed a significant increase in overall request costs, which is not observed in Table 5.4, so it is not significantly using more expensive modes. This is also in line with a smaller increase in the emission costs, indicating a less significant total use of a polluting truck. Because the modal splits are based on the transport leg and size of requests and not on the distance, it could be the case that under the reduced delay penalty more trucks are used in transshipments, thus causing the impression of a more significant modal shift towards trucks. But upon closer inspection of the number of transshipments and change in emissions, a reduced delay penalty in force majeure conditions could have a positive effect on the overall synchromodal performance.

5.4. Conclusion on Results & Analysis

The results from the planning and terminal perspective yielded slightly positive results. Even though no major improvements have been found in terms of planning success rate, planning costs, terminal total actions, and terminal total relocations, it is good to see that the integration of planning and terminal operations does not come at a big cost other than a computation increase. The results from the portion of served actions at terminals as well as the development of the dwell time at terminals throughout the iterations are impressive. Both show that the integration allows for good adaptability to the states of the terminals, ensuring both feasible and efficient planning can be achieved within a couple of MAS iterations.

The integrated MAS enables a detailed analysis of the influence of synchromodality on container terminals and vice versa. This is carried out through a scenario analysis, which tests the model under various disruption conditions. In total, 375 disruption tests were conducted under both normal and force majeure conditions, providing in-depth insights into the adaptability of synchromodality and the terminals within the network. Chapter 6 will discuss and synthesise these results.

6 Discussion

This chapter reflects on the key findings of the study by interpreting the results in relation to the research objectives and existing literature. It explores the managerial insights derived, highlighting their practical relevance and implications for industry stakeholders. The chapter also discusses the strengths and contributions of the study while acknowledging its limitations. Finally, it outlines directions for future research and offers recommendations for further improving the integration of synchromodal transport planning and container terminal operations.

6.1. Discussion on Results

This section discusses the performance of the proposed framework by examining the results related to computational efficiency, system integration, and response to disruptions. The findings highlighted the trade-off between increased computational complexity and improved decision-making capabilities.

The adapted Stacking Problem introduced higher computational demands, increasing execution times compared to the original SP, and also led to an increase in relocations due to stricter container placement constraints. Despite these challenges, the model remains computationally feasible within the context of this study and provided a more complete representation of terminal operations compared to classic container stacking optimisation models.

The integration of STPP-FS and the SP in the Multi-Agent System showed overall positive and promising results. The MAS showed an increase in execution time compared to the STPP-FS baseline, but this is primarily due to iterative terminal assessments and replanning. Apart from the increase in computational time, there were no other costs in terms of the objective performance of the planning and terminal agents. Both agents operated without hindrance to each other's objectives. The planning success rate, overall cost objective, and the number of terminal actions and relocations remained stable and even showed slight improvements through the MAS iterations. Regarding MAS performance itself, the integration yielded positive results in terms of the agents aligning on a feasible transport plan as well as on minimising the dwell time at terminals.

Finally, the scenario analysis produced interesting insights into how a synchromodal planner would adapt to disruptions and what effect these could have on container terminals. The two most notable findings were a decrease in the number of transshipments and a modal shift towards the faster, more flexible, but also more expensive and more polluting transport modes. These findings remained valid under the proposed force majeure conditions, where the consignee was more lenient toward delays caused by disruptions. However, these lenient conditions appeared to give the synchromodal planner greater flexibility and made it less dependent on the fastest and most flexible modes.

6.2. Managerial Insights

This section provides managerial insights derived from this research. These insights will be discussed and split between two perspectives, the first of which focuses on transport planning and the second on container terminal operations. A general managerial insight for all types of stakeholders is that integrating container operations into the planning phase can yield very positive results. Further insights highlight tendencies in response to disruptions and offer guidance for enhancing resilience without compromising long-term strategic goals.

6.2.1. Managerial Insights from the Planner's Perspective

Scenario analysis revealed a clear strategy adopted by the planning agent when mitigating disruptions, such as equipment failures or uncertainties in vehicle services. The results indicate an increase in overall and transport-specific costs, as well as emission-related costs. In contrast, it shows fewer storage days, transshipments, and container relocations. Interestingly, delay penalties remain relatively stable—suggesting that service levels are maintained, albeit through less sustainable means. This pattern implies that, under pressure, planners tend to prioritise fast, direct solutions, typically by switching to road transport, to meet delivery window constraints. While this ensures continuity and avoids penalties, it increases external costs and undermines modal shifts toward more sustainable alternatives.

The second part of the scenario analysis, under force majeure conditions, showed promising results in terms of optimising a synchromodal transport plan after a disruption. These promising results were observed under more lenient conditions in the disruption-adapted transport plan, which included either discounted delay penalties or extended delivery windows. The practical feasibility of these approaches remains uncertain since delivery windows depend not only on the consignee's leniency but also on the terminal and carrier in relation to demurrage and detention fees.

However, it could be interesting to explore how to redefine the concept of a delivery window in collaboration with the consignee, terminal, and shipper. One approach is to incorporate buffer time from the outset to proactively absorb potential delays, rather than extending the delivery window reactively. In the initial transport plan, prioritising early execution of the first leg could allow more flexibility in the event of a disruption, reducing the need for truck-based fallback options. Alternatively, dynamically recalibrating the cost weights, prioritising emissions reduction in the initial planning phase and shifting focus toward delay penalties in the event of a disruption could encourage planners to balance sustainability with service reliability, rather than defaulting to road transport.

6.2.2. Managerial Insights from the Terminal's Perspective

For container terminal operators, the scenario analysis shows a clear trend where the numbers of relocations and transshipments decrease. This reduction in workload may seem manageable when considering the drop in relocations, but it also reflects a diminished role of the terminal in the transport chain as planners become more constrained. Crucially, this is not a terminal-driven outcome but a result of upstream planning decisions. If planners adopted different delivery windows or cost structures, as discussed in the previous section, terminals might instead observe delayed (rather than cancelled) transshipments. This would lead to longer container dwell times and greater yard occupancy.

Terminals themselves could also take steps to provide planners with greater flexibility during disruptions or even under normal conditions. If flexible services are readily available between terminals, they could position themselves within the network as crucial transshipment nodes. The key takeaway for terminals is that their operational load during disruptions is highly uncertain and depends on two factors: the availability of non-road fallback options and the extent to which planners are incentivised to absorb delays rather than switch modes. Without these, a consistent drop in transshipment activity during disruptions can be expected.

6.3. Strengths and Contribution

This research makes several important contributions. First, it introduces a novel integration of synchromodal transport planning and container terminal operations, a combination that has received little attention in prior research. Second, it demonstrates the ability to simulate real-world uncertainties under different integration settings, providing a more realistic representation of operational challenges. Third, the study offers valuable insights into the impact of synchromodal integration on container terminal performance, generating practical implications for both researchers and industry practitioners.

6.4. Limitations

This section builds upon the previously noted limitations and assumptions from Section 3.6. First of all, the data limitations: this study builds upon the data from Y. Zhang et al., 2022a. This was of great use for this study, but it is limited in terms of only having shipments moving into the hinterland and not towards the port area. This has been slightly mitigated by the introduction of the fixed reverse flow in Section 4.3.4, but this only has an effect on the terminal agents.

Another prominent limitation in this study is related to computational scalability. The results and analysis showed increases in computational time as the problem size grew. All computational tests were performed on the same machine with the following specifications: 16 GB RAM, 13th Gen Intel® Core™ i7-13620H processor, 2.4 GHz, 10 cores. While this setup was sufficient for experimental purposes, it may not reflect performance on larger-scale, real-world systems. Future research could explore more powerful hardware or parallel computing techniques to enhance scalability, especially in networks with more agents.

Another limitation is related to the Stacking Problem proposed by Expósito-Izquierdo et al. (2015), and further adapted in this study. This model does not fully represent a real terminal. However, it was acceptable for the purpose of this study, given the adaptations made. With more powerful hardware, it would be interesting to explore alternative models that provide a more advanced simulation of container terminal operations.

Finally, the scenario analysis was conducted under L_1 settings, meaning that the planning agent only considered flexible truck services and fixed barge and train services. If flexible routing were introduced for barges, different behavioural outcomes might be observed. However, it remains unclear whether it is realistic to have barges readily available to adapt to disruptions. Barges are not as flexible as trucks, but allowing them to change routes midway could be an interesting option.

Despite these limitations, the findings provide valuable insights into the operational benefits of integrating stacking and transport planning in a MAS framework. The results suggest that synchromodal transport can enhance resilience, but its full potential depends on real-time adaptability and computationally efficient decision-making.

6.5. Future Work

For future work, the previously identified limitations could be addressed. In addition, research could focus on extending the formulation of disruptions. Different types of disruptions could be explored, or multiple disruptions could be incorporated within the same scenario to better reflect complex real-world situations. Introducing stochastic elements into the MAS would also be valuable. However, this would require substantially more computational power. Instead of relying on a single dynamic replanning moment, as used in this study's scenario analysis, it would necessitate a continuous replanning approach.

Additionally, the dynamic replanning component of the MAS was implemented using structured feedback loops rather than reinforcement learning (RL), which has been explored in related works. Future studies could integrate RL-based decision-making, allowing the system to learn from past disruptions and autonomously improve its planning efficiency over time.

7 Conclusion

Despite significant advances in logistics, global supply chains continue to face persistent challenges. Congestion, sustainability concerns, and vulnerability to disruptions have become major obstacles, affecting industries worldwide. Recent examples of such obstacles are the COVID-19 pandemic and the blockage of the Suez Canal, both of which placed supply chains under massive pressure. A promising approach to mitigating these challenges is synchromodality, which involves the synchronisation and seamless integration of multiple transport modes in the supply chain, allowing for dynamic adjustments based on real-time conditions. By leveraging data-driven decision-making and advanced coordination mechanisms, synchromodal transport aims to optimise freight movement while promoting sustainability and flexibility.

Synchromodality is a relatively new concept primarily studied at a conceptual level. Although some recent technical and quantitative studies have focused on planning and optimisation, aspects related to its impact on infrastructure, such as container terminal operations, remain underexplored. However, handling constraints, storage capacity, and congestion at terminals play a crucial role in creating a feasible transport plan. This research addresses this by developing a Multi-Agent System to model and evaluate the impact of integrating synchromodal transport with container terminal operations. Specifically, it seeks to answer the following research question:

> **”How does the integration of synchromodal transport planning and container terminal operations impact the efficiency of terminal operations, the adaptability of transport planning, and the overall cost-effectiveness of supply chain operations?”**

To address this, the research was guided by three sub-research questions, each of which is concluded upon below.

SQ.1: What are the key characteristics of synchromodality, and how do its complexities shape the integration of transport planning and container terminal operations?

Synchromodality is an advanced form of intermodal transport that allows dynamic mode selection based on real-time conditions, offering a higher level of flexibility than traditional multimodal systems. Its key characteristics include flexible mode selection, real-time data exchange, cost and time optimisation, environmental sustainability, collaboration among stakeholders, and (physical) infrastructure adaptations. Integrating these characteristics in planning with container terminal operations introduces complexities due to differences in operational constraints, stakeholder incentives, and decision-making processes.

To manage this complexity, this research applied a 5PL orchestrator structure, which centralises coordination between transport planners and terminal operators. The 5PL model acts as an intermediary, facilitating information exchange and optimising transport decisions based on both transport and terminal constraints. This structured approach minimises direct negotiation overheads while ensuring that synchromodal planning aligns with terminal operations. By adopting this 5PL-based coordination, the study demonstrated how improved integration reduced inefficiencies, minimised dwell times, and enhanced overall transport adaptability.

SQ.2: How can interactions between transport planners and terminal operators be modelled to simulate decision-making, coordination, and real-time adaptability in synchromodal transport?

To capture the complexities of decision-making in synchromodal transport, a Multi-Agent System was developed to model interactions between transport planning agents and container terminal agents. Transport planning agents were designed as practical reasoning agents, continuously optimising shipment schedules based on future states and adapting dynamically to disruptions. In contrast, terminal agents were modelled as reactive agents, responding to immediate constraints such as congestion and storage availability.

A key development of the MAS was the feedback loop through the service time matrix between the planning and terminal agents. This enabled information sharing between the agents and allowed the planning agent to make better-informed decisions. By integrating this feedback mechanism, the MAS provided an effective simulation environment to test different levels of collaboration and coordination. The integration yielded positive results in terms of the agents aligning on a feasible transport plan as well as on minimising the dwell time at terminals. Apart from the increase in computational time, there were no other costs in terms of the objective performance of the planning and terminal agents. Both agents operated without hindrance to each other's objectives. The planning success rate, overall cost objective, and the number of terminal actions and relocations remained stable and even showed slight improvements through the MAS iterations.

SQ.3: What real-world scenarios can be used to evaluate how the integration of synchromodal transport planning and container terminal operations impacts terminal efficiency, transport adaptability, and supply chain cost-effectiveness?

One of the key strengths of synchromodality lies in its ability to swiftly adapt to changing conditions, ensuring resilience and efficiency in logistics operations. To assess this adaptability, various disruption scenarios were tested, such as delays in barge and rail services or equipment failures. The integrated MAS enabled the opportunity to do a detailed analysis of the influence of synchromodality on container terminals and vice versa. This was carried out through a scenario analysis, which tests the model under various disruption conditions. In total, 375 disruption tests were conducted under both normal and force majeure conditions, providing in-depth insights into the adaptability of synchromodality and the terminals within the network.

The scenario analysis produced interesting insights into how a synchromodal planner would adapt to disruptions and what effect these could have on container terminals. The two most notable findings were a decrease in the number of transshipments and a modal shift towards the faster, more flexible, but also more expensive and more polluting transport modes. These findings remained valid under the proposed force majeure conditions, where the consignee was more lenient toward delays caused by disruptions. However, these lenient conditions appeared to give the synchromodal planner greater flexibility and made it less dependent on the fastest and most flexible modes.

To answer the main research question, the integration of synchromodal transport planning and container terminal operations showed promising results for creating a feasible transport plan, whose adaptability to disruptions is slightly enhanced by the increased integration, while having minimal impact on the terminal efficiency operations or the overall cost-effectiveness of supply chain operations.

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A

Setup Service Schedules

Table A.3: Truck schedules.

	Delta	Euromax	Home	Moerdijk	Venlo	Duisburg	Willebroek	Neuss	Dortmund	Nuremberg
Delta		[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]
Euromax			[10]	[11]	[12]	[13]	[14]	[15]	[16]	[17]
Home				[18]	[19]	[20]	[21]	[22]	[23]	[24]
Moerdijk					[25]	[26]	[27]			
Venlo						[28]		[29]	[30]	[31]
Duisburg								[32]	[33]	[34]
Willebroek										
Neuss										
Dortmund										
Nuremburg										

Note. Derived from (Y. Zhang et al., 2022a).

Table A.1: Barge schedules.

	Delta	Euromax	Home	Moerdijk	Venlo	Duisburg	Willebroek	Neuss	Dortmund	Nuremberg
Delta		53 > 54 [1]	53 > 55,5 [2]	3 > 8 [3] 15 > 20 [4] 27 > 32 [5] 39 > 44 [6] 51 > 56 [7] 63 > 68 [8] 75 > 80 [9] 87 > 92 [10] 99 > 104 [11] 111 > 116 [12] 123 > 128 [13] 135 > 140 [14] 147 > 152 [15] 159 > 164 [16]	12 > 25 [17] 18 > 31 [18] 36 > 49 [19] 42 > 55 [20] 60 > 73 [21] 66 > 79 [22] 90 > 103 [23] 96 > 109 [24] 120 > 133 [25]	82 > 98 [26] 102 > 118 [27]	68 > 79 [28] 98 > 109 [29] 146 > 157 [30]	80 > 97 [31]		
Euromax				3 > 8,5 [32] 51 > 56,5 [33] 99 > 104,5 [34]	27 > 40,5 [35] 75 > 88,5 [36]	103 > 119,5 [37]	112 > 123,5 [38]	66 > 83,5 [39]		
Home				5 > 8 [40] 53 > 56 [41] 101 > 104 [42]	99 > 110 [43] 126 > 137 [44]	51 > 66,5 [45]	20 > 30,5 [46]			
Moerdijk					95 > 105 [47]	71 > 83 [48]				
Venlo										
Duisburg								120 > 122.5 [49]		
Willebroek										
Neuss										
Dortmund										
Nuremburg										

Note. Derived from (Y. Zhang et al., 2022a).

Table A.2: Train schedules.

	Delta	Euromax	Home	Moerdijk	Venlo	Duisburg	Willebroek	Neuss	Dortmund	Nuremberg
Delta						41 > 47 [9] 75 > 81 [10] 99 > 105 [11] 113 > 119 [12]		33 > 37 [4] 57 > 61 [5] 110 > 115 [13]	9 > 13 [3] 16 > 20 [1] 40 > 44 [2] 88 > 95 [14]	51 > 66 [15] 81 > 85 [6] 99 > 114 [16] 105 > 109 [7] 129 > 133 [8]
Euromax						75 > 81.5 [19] 99 > 105.5 [20]		77 > 82.5 [21] 78 > 82.5 [17]	78 > 85.5 [22] 102 > 106.5 [18]	79 > 94.5 [23]
Home					86 > 89.5 [24]	27 > 32.5 [25] 75 > 80.5 [26]				
Moerdijk					75 > 78 [27]	77 > 81 [28]				
Venlo								112 > 113.5 [29]	113 > 115.5 [30]	114 > 125 [31]
Duisburg									121 > 122.5 [32]	122 > 132 [33]
Willebroek										
Neuss										
Dortmund										
Nuremburg										

Note. Derived from (Y. Zhang et al., 2022a).

B

STPP-FS Development


```
{0: {100001: {’quantity’: 10,
              ’delivery_start_time’: -1,
              ’delivery_end_time’: -1,
              ’pickup_start_time’: 35.00,
              ’pickup_end_time’: 35.10,
              ’reefer’: False,
              ’empty’: False,
              ’hazardous’: False,
              ’inbound’: None,
              ’outbound’: ’Barge1’},
     100002: {’quantity’: 18,
              ’delivery_start_time’: 15.00,
              ’delivery_end_time’: 15.20,
              ’pickup_start_time’: 35.10,
              ’pickup_end_time’: 35.30,
              ’reefer’: False,
              ’empty’: False,
              ’hazardous’: False,
              ’inbound’: ’Truck2’,
              ’outbound’: ’Barge1’}
    },
2:  {100002:  {’quantity’: 18,
              ’delivery_start_time’: -1,
              ’delivery_end_time’: -1,
              ’pickup_start_time’: 15.00,
              ’pickup_end_time’: 15.20,
              ’reefer’: False,
              ’empty’: False,
              ’hazardous’: False,
              ’inbound’: None,
              ’outbound’: ’Truck2’}
    },
6:  {100001: {’quantity’: 10,
              ’delivery_start_time’: 47.00,
              ’delivery_end_time’: 47.20,
              ’pickup_start_time’: 81.00,
              ’pickup_end_time’: 81.20,
              ’reefer’: False,
              ’empty’: False,
              ’hazardous’: False,
              ’inbound’: ’Barge1’,
              ’outbound’: ’Train1’},
     100002: {’quantity’: 18,
              ’delivery_start_time’:  47.20,
              ’delivery_end_time’: 47.50,
              ’pickup_start_time’: -1,
              ’pickup_end_time’: -1,
              ’reefer’: False,
              ’empty’: False,
              ’hazardous’: False,
```

```
                'inbound': 'Barge1',
                'outbound': None}
    },
9:  {100001: {'quantity': 10,
                'delivery_start_time': 81.00,
                'delivery_end_time': 81.20,
                'pickup_start_time': -1,
                'pickup_end_time': -1,
                'reefer': False,
                'empty': False,
                'hazardous': False,
                'inbound': 'Train1',
                'outbound': None}
    }
}
```

Listing B.1: STPP-FS Structured Output Example for Request 100001 and 100002

C

Model Development

Table C.1: Terminal configuration A.

Terminal (Nr.) Name	**Storage Configuration** Storage Type - Equipment - Stacks - Bays - Tiers - Capacity						**Handling Capacity** per hour
	Total Container Storage Capacity - General Container Storage Capacity						
(1) Delta	Barge	Gantry Crane	4	4	4	288	240
	Barge Buffer	Gantry	2	4	4	144	
	Empty	Stacker	8	1	8	64	
	Reefer	Gantry	6	2	5	60	
	Hazardous	Stacker	4	1	3	12	
	General	Gantry	6	10	6	360	
	Train	Gantry Crane	4	4	4	64	
	Train Buffer	Gantry Crane	2	4	4	32	
	Total Capacity = 1,024		General Capacity = 888				
(2) Euromax	Barge	Gantry Crane	4	3	4	48	160
	Barge Buffer	Gantry	2	3	4	24	
	Empty	Stacker	6	1	7	42	
	Reefer	Gantry	6	1	5	30	
	Hazardous	Stacker	4	1	3	12	
	General	Gantry	6	7	5	210	
	Train	Gantry Crane	4	2	4	32	
	Train Buffer	Gantry Crane	2	2	4	16	
	Total Capacity = 414		General Capacity = 330				
(3) Home	Barge	Gantry Crane	4	2	4	32	160
	Barge Buffer	Gantry	2	2	4	16	
	Empty	Stacker	6	1	7	42	
	Reefer	Gantry	4	1	4	16	
	Hazardous	Stacker	4	1	3	12	
	General	Gantry	6	6	5	180	
	Train	Gantry Crane	4	2	4	32	
	Train Buffer	Gantry Crane	2	2	4	16	
	Total Capacity = 346		General Capacity = 276				

Table C.1 continued below.

Terminal (Nr.) Name	**Storage Configuration** Storage Type	Equipment	Stacks	Bays	Tiers	Capacity	**Handling** Capacity p. hour
	Total Container Storage Capacity - General Container Storage Capacity						
(4) Moerdijk	Barge	Gantry Crane	4	2	4	32	90
	Barge Buffer	Gantry	2	2	4	16	
	Empty	Stacker	6	1	5	30	
	Reefer	Stacker	4	1	4	16	
	Hazardous	Stacker	4	1	3	12	
	General	Stacker	6	6	4	144	
	Train	Gantry Crane	4	1	4	16	
	Train Buffer	Gantry Crane	2	1	4	8	
	Total Capacity = 274		General Capacity = 216				
(5) Venlo	Barge	Gantry Crane	4	2	4	32	90
	Barge Buffer	Gantry	2	2	4	16	
	Empty	Stacker	6	1	5	30	
	Reefer	Stacker	4	1	4	16	
	Hazardous	Stacker	4	1	3	12	
	General	Stacker	6	6	4	144	
	Train	Gantry Crane	4	1	4	16	
	Train Buffer	Gantry Crane	2	1	4	8	
	Total Capacity = 274		General Capacity = 216				
(6) Duisburg	Barge	Gantry Crane	4	2	4	32	90
	Barge Buffer	Gantry	2	2	4	16	
	Empty	Stacker	6	1	5	30	
	Reefer	Stacker	4	1	4	16	
	Hazardous	Stacker	4	1	3	12	
	General	Stacker	6	6	4	144	
	Train	Gantry Crane	4	1	4	16	
	Train Buffer	Gantry Crane	2	1	4	8	
	Total Capacity = 274		General Capacity = 216				
(7) Willebroek	Barge	Gantry Crane	4	2	4	32	90
	Barge Buffer	Gantry	2	2	4	16	
	Empty	Stacker	6	1	5	30	
	Reefer	Stacker	4	1	4	16	
	Hazardous	Stacker	4	1	3	12	
	General	Stacker	6	6	4	144	
	Train	Gantry Crane	-	-	-	-	
	Train Buffer	Gantry Crane	-	-	-	-	
	Total Capacity = 250		General Capacity = 192				
(8) Neuss	Barge	Gantry Crane	4	2	4	32	90
	Barge Buffer	Gantry	2	2	4	16	
	Empty	Stacker	6	1	5	30	
	Reefer	Stacker	4	1	4	16	
	Hazardous	Stacker	4	1	3	12	
	General	Stacker	6	6	4	144	
	Train	Gantry Crane	4	1	4	16	
	Train Buffer	Gantry Crane	2	1	4	8	
	Total Capacity = 274		General Capacity = 216				

Table C.1 continued below.

Terminal (Nr.) Name	Storage Configuration Storage Type - Equipment - Stacks - Bays - Tiers - Capacity Total Container Storage Capacity - General Container Storage Capacity						Handling Capacity p. hour
(9) Dortmund	Barge	Gantry Crane	-	-	-	-	90
	Barge Buffer	Gantry	-	-	-	-	
	Empty	Stacker	6	1	5	30	
	Reefer	Stacker	4	1	4	16	
	Hazardous	Stacker	4	1	3	12	
	General	Stacker	6	6	4	144	
	Train	Gantry Crane	4	1	4	16	
	Train Buffer	Gantry Crane	2	1	4	8	
	Total Capacity = 226		General Capacity = 184				
(10) Nuremberg	Barge	Gantry Crane	-	-	-	-	90
	Barge Buffer	Gantry	-	-	-	-	
	Empty	Stacker	6	1	5	30	
	Reefer	Stacker	4	1	4	16	
	Hazardous	Stacker	4	1	3	12	
	General	Stacker	6	6	4	144	
	Train	Gantry Crane	4	1	4	16	
	Train Buffer	Gantry Crane	2	1	4	8	
	Total Capacity = 226		General Capacity = 184				

Table C.2: Terminal configuration B.

Terminal (Nr.) Name	Storage Configuration Storage Type - Equipment - Stacks - Bays - Tiers - Capacity Total Container Storage Capacity - General Container Storage Capacity						Handling Capacity per hour
(1) Delta	Barge	Gantry Crane	4	6	4	576	240
	Barge Buffer	Gantry	2	6	4	288	
	Empty	Stacker	8	3	8	192	
	Reefer	Gantry	6	3	5	90	
	Hazardous	Stacker	4	3	3	36	
	General	Gantry	6	18	6	648	
	Train	Gantry Crane	4	6	4	96	
	Train Buffer	Gantry Crane	2	6	4	48	
	Total Capacity = 1,974		General Capacity = 1,656				
(2) Euromax	Barge	Gantry Crane	4	4	4	384	160
	Barge Buffer	Gantry	2	4	4	192	
	Empty	Stacker	6	2	7	84	
	Reefer	Gantry	6	2	5	60	
	Hazardous	Stacker	4	2	3	24	
	General	Gantry	6	8	5	240	
	Train	Gantry Crane	4	4	4	64	
	Train Buffer	Gantry Crane	2	4	4	32	
	Total Capacity = 1,080		General Capacity = 912				

Table C.2 continued below.

Terminal (Nr.) Name	Storage Configuration Storage Type - Equipment - Stacks - Bays - Tiers - Capacity Total Container Storage Capacity - General Container Storage Capacity						Handling Capacity p. hour
(3) Home	Barge	Gantry Crane	4	3	4	288	160
	Barge Buffer	Gantry	2	3	4	144	
	Empty	Stacker	6	2	7	84	
	Reefer	Gantry	4	2	4	32	
	Hazardous	Stacker	4	2	3	24	
	General	Gantry	6	5	5	150	
	Train	Gantry Crane	4	4	4	64	
	Train Buffer	Gantry Crane	2	4	4	32	
	Total Capacity = 818		General Capacity = 710				
(4) Moerdijk	Barge	Gantry Crane	4	3	4	288	90
	Barge Buffer	Gantry	2	3	4	144	
	Empty	Stacker	6	1	5	30	
	Reefer	Stacker	4	1	4	16	
	Hazardous	Stacker	4	1	3	12	
	General	Stacker	6	5	4	120	
	Train	Gantry Crane	4	2	4	32	
	Train Buffer	Gantry Crane	2	2	4	16	
	Total Capacity = 658		General Capacity = 600				
(5) Venlo	Barge	Gantry Crane	4	3	4	288	90
	Barge Buffer	Gantry	2	3	4	144	
	Empty	Stacker	6	1	5	30	
	Reefer	Stacker	4	1	4	16	
	Hazardous	Stacker	4	1	3	12	
	General	Stacker	6	5	4	120	
	Train	Gantry Crane	4	2	4	32	
	Train Buffer	Gantry Crane	2	2	4	16	
	Total Capacity = 658		General Capacity = 600				
(6) Duisburg	Barge	Gantry Crane	4	3	4	288	90
	Barge Buffer	Gantry	2	3	4	144	
	Empty	Stacker	6	1	5	30	
	Reefer	Stacker	4	1	4	16	
	Hazardous	Stacker	4	1	3	12	
	General	Stacker	6	5	4	120	
	Train	Gantry Crane	4	2	4	32	
	Train Buffer	Gantry Crane	2	2	4	16	
	Total Capacity = 658		General Capacity = 600				
(7) Willebroek	Barge	Gantry Crane	4	3	4	288	90
	Barge Buffer	Gantry	2	3	4	144	
	Empty	Stacker	6	1	5	30	
	Reefer	Stacker	4	1	4	16	
	Hazardous	Stacker	4	1	3	12	
	General	Stacker	6	12	4	288	
	Train	Gantry Crane	-	-	-	-	
	Train Buffer	Gantry Crane	-	-	-	-	
	Total Capacity = 778		General Capacity = 720				

Table C.2 continued below.

Terminal (Nr.) Name	Storage Configuration Storage Type - Equipment - Stacks - Bays - Tiers - Capacity Total Container Storage Capacity - General Container Storage Capacity						Handling Capacity p. hour
(8) Neuss	Barge	Gantry Crane	4	3	4	288	90
	Barge Buffer	Gantry	2	3	4	144	
	Empty	Stacker	6	1	5	30	
	Reefer	Stacker	4	1	4	16	
	Hazardous	Stacker	4	1	3	12	
	General	Stacker	6	5	4	120	
	Train	Gantry Crane	4	2	4	32	
	Train Buffer	Gantry Crane	2	2	4	16	
	Total Capacity = 658		General Capacity = 600				
(9) Dortmund	Barge	Gantry Crane	-	-	-	-	90
	Barge Buffer	Gantry	-	-	-	-	
	Empty	Stacker	6	1	5	30	
	Reefer	Stacker	4	1	4	16	
	Hazardous	Stacker	4	1	3	12	
	General	Stacker	6	8	4	192	
	Train	Gantry Crane	4	2	4	32	
	Train Buffer	Gantry Crane	2	2	4	16	
	Total Capacity = 298		General Capacity = 256				
(10) Nuremburg	Barge	Gantry Crane	-	-	-	-	90
	Barge Buffer	Gantry	-	-	-	-	
	Empty	Stacker	6	1	5	30	
	Reefer	Stacker	4	1	4	16	
	Hazardous	Stacker	4	1	3	12	
	General	Stacker	6	8	4	192	
	Train	Gantry Crane	4	2	4	32	
	Train Buffer	Gantry Crane	2	2	4	16	
	Total Capacity = 298		General Capacity = 256				

Table C.3: Terminal configuration C.

Terminal (Nr.) Name	Storage Configuration Storage Type - Equipment - Stacks - Bays - Tiers - Capacity Total Container Storage Capacity - General Container Storage Capacity						Handling Capacity per hour
(1) Delta	Barge	Gantry Crane	4	10	4	960	240
	Barge Buffer	Gantry	2	10	4	480	
	Empty	Stacker	8	3	8	192	
	Reefer	Gantry	6	4	5	120	
	Hazardous	Stacker	4	3	3	36	
	General	Gantry	6	30	6	1,080	
	Train	Gantry Crane	4	10	4	160	
	Train Buffer	Gantry Crane	2	10	4	80	
	Total Capacity = 3,108		General Capacity = 2,760				

Table C.3 continued below.

Terminal (Nr.) Name	Storage Configuration: Storage Type - Equipment - Stacks - Bays - Tiers - Capacity; Total Container Storage Capacity - General Container Storage Capacity						Handling Capacity p. hour
(2) Euromax	Barge	Gantry Crane	4	6	4	576	160
	Barge Buffer	Gantry	2	6	4	288	
	Empty	Stacker	6	2	7	84	
	Reefer	Gantry	6	3	5	90	
	Hazardous	Stacker	4	2	3	24	
	General	Gantry	6	12	5	360	
	Train	Gantry Crane	4	6	4	96	
	Train Buffer	Gantry Crane	2	6	4	48	
	Total Capacity = 1,566		General Capacity = 1,368				
(3) Home	Barge	Gantry Crane	4	5	4	480	160
	Barge Buffer	Gantry	2	5	4	240	
	Empty	Stacker	6	2	7	84	
	Reefer	Gantry	4	3	4	48	
	Hazardous	Stacker	4	2	3	24	
	General	Gantry	6	6	5	180	
	Train	Gantry Crane	4	5	4	80	
	Train Buffer	Gantry Crane	2	5	4	40	
	Total Capacity = 1,176		General Capacity = 1,020				
(4) Moerdijk	Barge	Gantry Crane	4	5	4	480	90
	Barge Buffer	Gantry	2	5	4	240	
	Empty	Stacker	6	2	5	60	
	Reefer	Stacker	4	2	4	32	
	Hazardous	Stacker	4	2	3	24	
	General	Stacker	6	26	4	624	
	Train	Gantry Crane	4	5	4	80	
	Train Buffer	Gantry Crane	2	5	4	40	
	Total Capacity = 1,580		General Capacity = 1,464				
(5) Venlo	Barge	Gantry Crane	4	4	4	384	90
	Barge Buffer	Gantry	2	4	4	192	
	Empty	Stacker	6	2	5	60	
	Reefer	Stacker	4	2	4	32	
	Hazardous	Stacker	4	2	3	24	
	General	Stacker	6	10	4	240	
	Train	Gantry Crane	4	3	4	48	
	Train Buffer	Gantry Crane	2	3	4	24	
	Total Capacity = 1,000		General Capacity = 888				
(6) Duisburg	Barge	Gantry Crane	4	4	4	384	90
	Barge Buffer	Gantry	2	4	4	192	
	Empty	Stacker	6	2	5	60	
	Reefer	Stacker	4	2	4	32	
	Hazardous	Stacker	4	2	3	24	
	General	Stacker	6	8	4	192	
	Train	Gantry Crane	4	3	4	48	
	Train Buffer	Gantry Crane	2	3	4	24	
	Total Capacity = 956		General Capacity = 864				

Table C.3 continued below.

Terminal (Nr.) Name	Storage Configuration Storage Type - Equipment - Stacks - Bays - Tiers - Capacity Total Container Storage Capacity - General Container Storage Capacity						Handling Capacity p. hour
(7) Willebroek	Barge	Gantry Crane	4	4	4	384	90
	Barge Buffer	Gantry	2	4	4	192	
	Empty	Stacker	6	2	5	60	
	Reefer	Stacker	4	2	4	32	
	Hazardous	Stacker	4	2	3	24	
	General	Stacker	6	10	4	240	
	Train	Gantry Crane	-	-	-	-	
	Train Buffer	Gantry Crane	-	-	-	-	
	Total Capacity = 932		General Capacity = 840				
(8) Neuss	Barge	Gantry Crane	4	4	4	384	90
	Barge Buffer	Gantry	2	4	4	192	
	Empty	Stacker	6	2	5	60	
	Reefer	Stacker	4	2	4	32	
	Hazardous	Stacker	4	2	3	24	
	General	Stacker	6	10	4	240	
	Train	Gantry Crane	4	3	4	48	
	Train Buffer	Gantry Crane	2	3	4	24	
	Total Capacity = 1,004		General Capacity = 912				
(9) Dortmund	Barge	Gantry Crane	-	-	-	-	90
	Barge Buffer	Gantry	-	-	-	-	
	Empty	Stacker	6	2	5	60	
	Reefer	Stacker	4	2	4	32	
	Hazardous	Stacker	4	2	3	24	
	General	Stacker	6	8	4	192	
	Train	Gantry Crane	4	3	4	48	
	Train Buffer	Gantry Crane	2	3	4	24	
	Total Capacity = 380		General Capacity = 288				
(10) Nuremburg	Barge	Gantry Crane	-	-	-	-	90
	Barge Buffer	Gantry	-	-	-	-	
	Empty	Stacker	6	2	5	60	
	Reefer	Stacker	4	2	4	32	
	Hazardous	Stacker	4	2	3	24	
	General	Stacker	6	6	4	144	
	Train	Gantry Crane	4	3	4	48	
	Train Buffer	Gantry Crane	2	3	4	24	
	Total Capacity = 332		General Capacity = 240				

Table C.4: Terminal configuration D.

Terminal (Nr.) Name	**Storage Configuration** Storage Type	Equipment	Stacks	Bays	Tiers	Capacity	**Handling Capacity** per hour
	Total Container Storage Capacity - General Container Storage Capacity						
(1) Delta	Barge	Gantry Crane	4	12	4	1,152	240
	Barge Buffer	Gantry	2	12	4	576	
	Empty	Stacker	8	5	8	320	
	Reefer	Gantry	6	6	5	180	
	Hazardous	Stacker	4	5	3	60	
	General	Gantry	6	72	6	2,592	
	Train	Gantry Crane	4	12	4	192	
	Train Buffer	Gantry Crane	2	12	4	96	
	Total Capacity = 5,168		General Capacity = 4,608				
(2) Euromax	Barge	Gantry Crane	4	8	4	768	160
	Barge Buffer	Gantry	2	8	4	384	
	Empty	Stacker	6	3	7	126	
	Reefer	Gantry	6	5	5	150	
	Hazardous	Stacker	4	3	3	36	
	General	Gantry	6	18	5	540	
	Train	Gantry Crane	4	8	4	128	
	Train Buffer	Gantry Crane	2	8	4	64	
	Total Capacity = 2,196		General Capacity = 1,884				
(3) Home	Barge	Gantry Crane	4	8	4	768	160
	Barge Buffer	Gantry	2	8	4	384	
	Empty	Stacker	6	3	7	126	
	Reefer	Gantry	4	5	4	80	
	Hazardous	Stacker	4	3	3	36	
	General	Gantry	6	18	5	540	
	Train	Gantry Crane	4	8	4	128	
	Train Buffer	Gantry Crane	2	8	4	64	
	Total Capacity = 2,126		General Capacity = 1,964				
(4) Moerdijk	Barge	Gantry Crane	4	6	4	576	90
	Barge Buffer	Gantry	2	6	4	288	
	Empty	Stacker	6	2	5	60	
	Reefer	Stacker	4	3	4	48	
	Hazardous	Stacker	4	2	3	24	
	General	Stacker	6	10	4	240	
	Train	Gantry Crane	4	6	4	96	
	Train Buffer	Gantry Crane	2	6	4	48	
	Total Capacity = 1,380		General Capacity = 1,248				
(5) Venlo	Barge	Gantry Crane	4	6	4	576	90
	Barge Buffer	Gantry	2	6	4	288	
	Empty	Stacker	6	2	5	60	
	Reefer	Stacker	4	3	4	48	
	Hazardous	Stacker	4	2	3	24	
	General	Stacker	6	10	4	240	
	Train	Gantry Crane	4	6	4	96	
	Train Buffer	Gantry Crane	2	6	4	48	
	Total Capacity = 1,380		General Capacity = 1,248				

Table C.4 continued below.

Terminal (Nr.) Name	Storage Configuration: Storage Type	Equipment	Stacks	Bays	Tiers	Capacity	Handling Capacity p. hour
	Total Container Storage Capacity - General Container Storage Capacity						
(6) Duisburg	Barge	Gantry Crane	4	6	4	576	90
	Barge Buffer	Gantry	2	6	4	288	
	Empty	Stacker	6	2	5	60	
	Reefer	Stacker	4	3	4	48	
	Hazardous	Stacker	4	2	3	24	
	General	Stacker	6	20	4	480	
	Train	Gantry Crane	4	6	4	96	
	Train Buffer	Gantry Crane	2	6	4	48	
	Total Capacity = 1,620		General Capacity = 1,536				
(7) Willebroek	Barge	Gantry Crane	4	6	4	576	90
	Barge Buffer	Gantry	2	6	4	288	
	Empty	Stacker	6	2	5	60	
	Reefer	Stacker	4	3	4	48	
	Hazardous	Stacker	4	2	3	24	
	General	Stacker	6	36	4	864	
	Train	Gantry Crane	-	-	-	-	
	Train Buffer	Gantry Crane	-	-	-	-	
	Total Capacity = 1,860		General Capacity = 1,728				
(8) Neuss	Barge	Gantry Crane	4	6	4	576	90
	Barge Buffer	Gantry	2	6	4	288	
	Empty	Stacker	6	2	5	60	
	Reefer	Stacker	4	3	4	48	
	Hazardous	Stacker	4	2	3	24	
	General	Stacker	6	36	4	864	
	Train	Gantry Crane	4	6	4	96	
	Train Buffer	Gantry Crane	2	6	4	48	
	Total Capacity = 2,004		General Capacity = 1,920				
(9) Dortmund	Barge	Gantry Crane	-	-	-	-	90
	Barge Buffer	Gantry	-	-	-	-	
	Empty	Stacker	6	2	5	60	
	Reefer	Stacker	4	3	4	48	
	Hazardous	Stacker	4	2	3	24	
	General	Stacker	6	28	4	672	
	Train	Gantry Crane	4	6	4	96	
	Train Buffer	Gantry Crane	2	6	4	48	
	Total Capacity = 948		General Capacity = 864				
(10) Nuremburg	Barge	Gantry Crane	-	-	-	-	90
	Barge Buffer	Gantry	-	-	-	-	
	Empty	Stacker	6	2	5	60	
	Reefer	Stacker	4	3	4	48	
	Hazardous	Stacker	4	2	3	24	
	General	Stacker	6	16	4	384	
	Train	Gantry Crane	4	6	4	96	
	Train Buffer	Gantry Crane	2	6	4	48	
	Total Capacity = 660		General Capacity = 624				

Table C.5: Terminal configuration E.

Terminal (Nr.) Name	Storage Configuration: Storage Type	Equipment	Stacks	Bays	Tiers	Capacity	Handling Capacity per hour
	Total Container Storage Capacity - General Container Storage Capacity						
(1) Delta	Barge	Gantry Crane	4	24	4	3,072	240
	Barge Buffer	Gantry	2	24	4	1,536	
	Empty	Stacker	8	8	8	512	
	Reefer	Gantry	6	10	5	300	
	Hazardous	Stacker	4	8	3	96	
	General	Gantry	6	144	6	5,184	
	Train	Gantry Crane	4	24	4	384	
	Train Buffer	Gantry Crane	2	24	4	192	
	Total Capacity = 11,276		General Capacity = 10,368				
(2) Euromax	Barge	Gantry Crane	4	16	4	2,048	160
	Barge Buffer	Gantry	2	16	4	1,024	
	Empty	Stacker	6	6	7	252	
	Reefer	Gantry	6	8	5	240	
	Hazardous	Stacker	4	6	3	72	
	General	Gantry	6	48	5	1,440	
	Train	Gantry Crane	4	16	4	256	
	Train Buffer	Gantry Crane	2	16	4	128	
	Total Capacity = 5,460		General Capacity = 4,896				
(3) Home	Barge	Gantry Crane	4	10	4	1,280	160
	Barge Buffer	Gantry	2	10	4	640	
	Empty	Stacker	6	6	7	252	
	Reefer	Gantry	4	8	4	128	
	Hazardous	Stacker	4	6	3	72	
	General	Gantry	6	42	5	1,260	
	Train	Gantry Crane	4	10	4	160	
	Train Buffer	Gantry Crane	2	10	4	80	
	Total Capacity = 3,872		General Capacity = 3,420				
(4) Moerdijk	Barge	Gantry Crane	4	10	4	1,280	90
	Barge Buffer	Gantry	2	10	4	640	
	Empty	Stacker	6	4	5	120	
	Reefer	Stacker	4	6	4	96	
	Hazardous	Stacker	4	4	3	48	
	General	Stacker	6	42	4	1,008	
	Train	Gantry Crane	4	10	4	160	
	Train Buffer	Gantry Crane	2	10	4	80	
	Total Capacity = 3,432		General Capacity = 3,168				
(5) Venlo	Barge	Gantry Crane	4	10	4	1,280	90
	Barge Buffer	Gantry	2	10	4	640	
	Empty	Stacker	6	4	5	120	
	Reefer	Stacker	4	6	4	96	
	Hazardous	Stacker	4	4	3	48	
	General	Stacker	6	42	4	1,008	
	Train	Gantry Crane	4	10	4	160	
	Train Buffer	Gantry Crane	2	10	4	80	
	Total Capacity = 3,432		General Capacity = 3,168				

Table C.5 continued below.

Terminal (Nr.) Name	Storage Configuration Storage Type - Equipment - Stacks - Bays - Tiers - Capacity Total Container Storage Capacity - General Container Storage Capacity						Handling Capacity p. hour
(6) Duisburg	Barge	Gantry Crane	4	10	4	1,280	90
	Barge Buffer	Gantry	2	10	4	640	
	Empty	Stacker	6	4	5	120	
	Reefer	Stacker	4	6	4	96	
	Hazardous	Stacker	4	4	3	48	
	General	Stacker	6	42	4	1,008	
	Train	Gantry Crane	4	10	4	160	
	Train Buffer	Gantry Crane	2	10	4	80	
	Total Capacity = 3,432		General Capacity = 3,168				
(7) Willebroek	Barge	Gantry Crane	4	10	4	1,280	90
	Barge Buffer	Gantry	2	10	4	640	
	Empty	Stacker	6	4	5	120	
	Reefer	Stacker	4	6	4	96	
	Hazardous	Stacker	4	4	3	48	
	General	Stacker	6	72	4	1,728	
	Train	Gantry Crane	-	-	-	-	
	Train Buffer	Gantry Crane	-	-	-	-	
	Total Capacity = 3,912		General Capacity = 3,648				
(8) Neuss	Barge	Gantry Crane	4	10	4	1,280	90
	Barge Buffer	Gantry	2	10	4	640	
	Empty	Stacker	6	4	5	120	
	Reefer	Stacker	4	6	4	96	
	Hazardous	Stacker	4	4	3	48	
	General	Stacker	6	42	4	1,008	
	Train	Gantry Crane	4	10	4	160	
	Train Buffer	Gantry Crane	2	10	4	80	
	Total Capacity = 3,432		General Capacity = 3,168				
(9) Dortmund	Barge	Gantry Crane	-	-	-	-	90
	Barge Buffer	Gantry	-	-	-	-	
	Empty	Stacker	6	4	5	120	
	Reefer	Stacker	4	6	4	96	
	Hazardous	Stacker	4	4	3	48	
	General	Stacker	6	54	4	1,296	
	Train	Gantry Crane	4	10	4	160	
	Train Buffer	Gantry Crane	2	10	4	80	
	Total Capacity = 1,800		General Capacity = 1,536				
(10) Nuremburg	Barge	Gantry Crane	-	-	-	-	90
	Barge Buffer	Gantry	-	-	-	-	
	Empty	Stacker	6	4	5	120	
	Reefer	Stacker	4	6	4	96	
	Hazardous	Stacker	4	4	3	48	
	General	Stacker	6	54	4	1,296	
	Train	Gantry Crane	4	10	4	160	
	Train Buffer	Gantry Crane	2	10	4	80	
	Total Capacity = 1,800		General Capacity = 1,536				

D

Scenario Results

Table D.1: Equipment failure A: absolute values.

Disruption		Planning Agent								Terminal Agent		Modal Split		
Terminal Config	Notification Delay	Overall	Request	Wait	Trans-shipment	(Un)loading	Emission	Storage	Delay	Reshuffles	Trans-shipments	Barge	Train	Truck
A	0	7102.18 p=0.306	2499.09 p=0.062	-0.52 p=0.257	-1052.80 p=0.036	-246.40 p=0.232	10.78 p=0.026	-1.58 p=0.992	5893.60 p=0.364	-8.00 p=0.838	-32.20 p=0.045	-0.00 p=0.889	0.00 p=0.979	0.00 p=0.862
A	+4	2790.57 p=0.021	3094.48 p=0.024	-0.69 p=0.063	-890.40 p=0.059	-382.80 p=0.125	11.45 p=0.029	166.53 p=0.379	792.00 p=0.046	38.40 p=0.190	-25.60 p=0.076	-0.03 p=0.138	0.02 p=0.215	0.01 p=0.356
A	+8	14186.36 p=0.064	4638.48 p=0.040	-0.69 p=0.054	-1103.20 p=0.003	-338.40 p=0.200	13.14 p=0.121	607.42 p=0.007	10369.60 p=0.184	-10.00 p=0.847	-34.80 p=0.010	-0.04 p=0.079	0.04 p=0.106	-0.00 p=0.929
E	0	341.44 p=0.435	1920.31 p=0.016	-0.59 p=0.073	-1215.20 p=0.001	-233.20 p=0.133	9.25 p=0.039	-57.13 p=0.569	-82.00 p=0.002	-0.60 p=0.818	-39.80 p=0.001	-0.00 p=0.545	0.01 p=0.184	-0.01 p=0.433
E	+4	8773.43 p=0.283	2863.56 p=0.031	-1.06 p=0.030	-1318.40 p=0.011	-497.20 p=0.224	14.53 p=0.012	-37.60 p=0.890	7749.60 p=0.365	-0.60 p=0.810	-40.40 p=0.012	-0.02 p=0.182	0.02 p=0.229	0.00 p=0.786
E	+8	4883.19 p=0.201	3363.17 p=0.023	-0.88 p=0.024	-1153.60 p=0.061	-492.40 p=0.138	8.24 p=0.227	448.46 p=0.116	2710.20 p=0.335	0.40 p=0.704	-30.00 p=0.098	-0.00 p=0.909	0.00 p=0.708	-0.00 p=0.746
A*	0	-2450.62 p=0.067	937.51 p=0.107	-0.54 p=0.238	-1590.40 p=0.010	-570.40 p=0.218	-10.05 p=0.217	-96.75 p=0.744	-1120.00 p<0.001	68.80 p=0.172	-19.40 p=0.270	-0.01 p=0.562	0.01 p=0.612	0.00 p=0.717
A*	+4	-3355.86 p=0.336	-1428.21 p=0.701	-0.85 p=0.013	-1064.00 p=0.105	-246.40 p=0.592	1.65 p=0.827	501.94 p=0.178	-1120.00 p<0.001	-1.60 p=0.937	-0.60 p=0.977	-0.01 p=0.319	0.01 p=0.470	0.00 p=0.845
A*	+8	-1909.24 p=0.666	-265.07 p=0.951	-1.78 p=0.016	-767.20 p=0.011	-1201.20 p=0.062	51.10 p=0.097	809.31 p=0.079	-534.40 p=0.413	-13.00 p=0.612	0.80 p=0.925	-0.05 p=0.027	0.02 p=0.415	0.03 p=0.093
A**	0	6016.38 p=0.422	2797.14 p=0.005	-1.40 p=0.008	-1416.80 p=0.019	-1129.20 p=0.017	9.16 p=0.435	-347.36 p=0.240	6104.84 p=0.386	-12.60 p=0.804	-21.20 p=0.200	-0.02 p=0.212	0.01 p=0.701	0.02 p=0.102
A**	+4	-14744.63 p=0.414	-16497.41 p=0.428	-1.21 p=0.145	-1187.20 p=0.023	-1178.80 p=0.196	39.79 p=0.301	49.41 p=0.751	4030.79 p=0.288	-38.80 p=0.552	-8.60 p=0.207	-0.03 p=0.414	0.00 p=0.852	0.02 p=0.435
A**	+8	1797.53 p=0.683	1380.12 p=0.418	-0.99 p=0.019	-834.40 p=0.138	-1322.40 p<0.001	-0.86 p=0.959	187.86 p=0.704	2388.20 p=0.373	-110.40 p=0.077	7.60 p=0.716	-0.01 p=0.354	-0.01 p=0.577	0.02 p=0.281
A***	0	3527.24 p=0.302	2335.49 p=0.011	-0.40 p=0.035	-1226.40 p=0.009	-22.00 p=0.924	8.58 p=0.007	-38.84 p=0.856	2470.80 p=0.436	11.00 p=0.707	-28.40 p=0.126	-0.01 p=0.515	0.01 p=0.356	-0.01 p=0.191
A***	+4	2643.99 p=0.284	2709.13 p<0.001	-0.86 p=0.031	-991.20 p<0.001	-541.20 p=0.112	13.53 p=0.007	-102.20 p=0.615	1556.80 p=0.490	69.00 p=0.084	-8.80 p=0.232	-0.01 p=0.176	0.00 p=1.000	0.01 p=0.162
A***	+8	-12992.53 p=0.421	-12062.53 p=0.490	-2.09 p=0.028	-1612.80 p=0.021	-1608.80 p=0.038	43.72 p=0.260	383.38 p=0.196	1866.60 p=0.465	-49.20 p=0.541	-28.60 p=0.167	-0.06 p=0.018	0.02 p=0.359	0.04 p=0.166

Note: A*: Terminal Configuration A, under Force Majeure, delay penalty - 10%, A**: Terminal Configuration A, under Force Majeure, delay penalty - 50%, A***: Terminal Configuration A, under Force Majeure, extended delivery window +24h.

Table D.2: Equipment failure A: percentage changes.

Disruption		Planning Agent								Terminal Agent		Modal Split		
Terminal Config	Notification Delay	Overall	Request	Wait	Trans-shipment	(Un)loading	Emission	Storage	Delay	Reshuffles	Trans-shipments	Barge	Train	Truck
A	0	9.7% p=0.306	6.7% p=0.062	-3.1% p=0.257	-13.7% p=0.036	-1.1% p=0.232	2.2% p=0.026	-0.0% p=0.992	526.2% p=0.364	-0.4% p=0.838	-13.6% p=0.045	-0.12pp p=0.889	0.03pp p=0.979	0.09pp p=0.862
A	+4	3.8% p=0.021	8.3% p=0.024	-4.1% p=0.063	-11.6% p=0.059	-1.8% p=0.125	2.3% p=0.029	3.7% p=0.379	70.7% p=0.046	1.8% p=0.190	-10.8% p=0.076	-2.61pp p=0.138	2.04pp p=0.215	0.57pp p=0.356
A	+8	19.4% p=0.064	12.4% p=0.040	-4.1% p=0.054	-14.3% p=0.003	-1.6% p=0.200	2.7% p=0.121	13.6% p=0.007	925.9% p=0.184	-0.5% p=0.847	-14.6% p=0.010	-3.84pp p=0.079	3.93pp p=0.106	-0.08pp p=0.929
E	0	0.5% p=0.435	5.1% p=0.016	-3.5% p=0.073	-15.8% p=0.001	-1.1% p=0.133	1.9% p=0.039	-1.3% p=0.569	-7.3% p=0.002	-1.4% p=0.818	-16.7% p=0.001	-0.23pp p=0.545	0.80pp p=0.184	-0.57pp p=0.433
E	+4	12.0% p=0.283	7.6% p=0.031	-6.3% p=0.030	-17.1% p=0.011	-2.3% p=0.224	3.0% p=0.012	-0.8% p=0.890	691.9% p=0.365	-1.6% p=0.810	-16.9% p=0.012	-1.90pp p=0.182	1.55pp p=0.229	0.36pp p=0.786
E	+8	6.7% p=0.201	9.0% p=0.023	-5.3% p=0.024	-15.0% p=0.061	-2.3% p=0.138	1.7% p=0.227	10.0% p=0.116	242.0% p=0.335	1.1% p=0.704	-12.6% p=0.098	-0.12pp p=0.909	0.50pp p=0.708	-0.38pp p=0.746
A*	0	-3.4% p=0.067	2.5% p=0.107	-3.2% p=0.238	-20.7% p=0.010	-2.6% p=0.218	-2.1% p=0.217	-2.2% p=0.744	-100.0% p<0.001	3.5% p=0.172	-8.2% p=0.270	-1.03pp p=0.562	0.76pp p=0.612	0.27pp p=0.717
A*	+4	-4.6% p=0.336	-3.8% p=0.701	-5.1% p=0.013	-13.8% p=0.105	-1.1% p=0.592	0.3% p=0.827	11.2% p=0.178	-100.0% p<0.001	-0.1% p=0.937	-0.3% p=0.977	-1.42pp p=0.319	1.13pp p=0.470	0.29pp p=0.845
A*	+8	-2.6% p=0.666	-0.7% p=0.951	-10.6% p=0.016	-10.0% p=0.011	-5.5% p=0.062	10.5% p=0.097	18.1% p=0.079	-47.7% p=0.413	-0.7% p=0.612	0.3% p=0.925	-5.01pp p=0.027	1.56pp p=0.415	3.45pp p=0.093
A**	0	8.2% p=0.422	7.5% p=0.005	-8.3% p=0.008	-18.4% p=0.019	-5.2% p=0.017	1.9% p=0.435	-7.8% p=0.240	545.1% p=0.386	-0.6% p=0.804	-8.9% p=0.200	-2.40pp p=0.212	0.58pp p=0.701	1.82pp p=0.102
A**	+4	-20.2% p=0.414	-44.1% p=0.428	-7.2% p=0.145	-15.4% p=0.023	-5.4% p=0.196	8.2% p=0.301	1.1% p=0.751	359.9% p=0.288	-1.9% p=0.552	-3.6% p=0.207	-2.66pp p=0.414	0.20pp p=0.852	2.47pp p=0.435
A**	+8	2.5% p=0.683	3.7% p=0.418	-5.9% p=0.019	-10.8% p=0.138	-6.1% p<0.001	-0.2% p=0.959	4.2% p=0.704	213.2% p=0.373	-5.7% p=0.077	3.2% p=0.716	-1.39pp p=0.354	-0.70pp p=0.577	2.09pp p=0.281
A***	0	4.8% p=0.302	6.2% p=0.011	-2.4% p=0.035	-15.9% p=0.009	-0.1% p=0.924	1.8% p=0.007	-0.9% p=0.856	220.6% p=0.436	0.6% p=0.707	-12.0% p=0.126	-0.60pp p=0.515	1.30pp p=0.356	-0.70pp p=0.191
A***	+4	3.6% p=0.284	7.2% p<0.001	-5.2% p=0.031	-12.9% p<0.001	-2.5% p=0.112	2.8% p=0.007	-2.3% p=0.615	139.0% p=0.490	3.5% p=0.084	-3.7% p=0.232	-1.12pp p=0.176	0.00pp p=1.000	1.12pp p=0.162
A***	+8	-17.8% p=0.421	-32.2% p=0.490	-12.5% p=0.028	-20.9% p=0.021	-7.4% p=0.038	9.0% p=0.260	8.6% p=0.196	166.7% p=0.465	-2.5% p=0.541	-12.0% p=0.167	-6.00pp p=0.018	2.14pp p=0.359	3.86pp p=0.166

Note: A*: Terminal Configuration A, under Force Majeure, delay penalty - 10%, A**: Terminal Configuration A, under Force Majeure, delay penalty - 50%, A***: Terminal Configuration A, under Force Majeure, extended delivery window +24h.

Table D.3: Equipment failure B: absolute values.

Disruption		Planning Agent								Terminal Agent		Modal Split		
Terminal Config	Notification Delay	Overall	Request	Wait	Trans-shipment	(Un)loading	Emission	Storage	Delay	Reshuffles	Trans-shipments	Barge	Train	Truck
A	0	2135.60 p=0.014	3808.17 p=0.002	-1.99 p=0.002	-1831.20 p<0.001	22.00 p=0.923	10.28 p=0.001	-127.65 p=0.445	256.00 p=0.267	42.60 p=0.238	-57.80 p=0.002	-0.04 p=0.049	0.04 p<0.001	-0.01 p=0.559
A	+4	6875.30 p=0.252	3641.73 p=0.009	-2.23 p=0.003	-1635.20 p=0.016	-780.40 p=0.013	10.96 p=0.106	144.84 p=0.601	5495.60 p=0.365	-76.80 p=0.084	-47.60 p=0.024	-0.04 p=0.026	0.03 p=0.019	0.01 p=0.378
A	+8	6866.80 p=0.479	1690.59 p=0.265	-2.25 p<0.001	-1653.60 p=0.022	-926.00 p=0.004	-2.75 p=0.879	-106.78 p=0.725	7867.60 p=0.378	-22.80 p=0.542	-51.60 p=0.048	-0.04 p=0.063	0.04 p=0.012	-0.00 p=0.862
E	0	7349.16 p=0.263	3586.31 p=0.006	-1.45 p=0.021	-1803.20 p=0.003	-334.40 p=0.469	17.03 p=0.077	-34.73 p=0.896	5919.60 p=0.363	-0.80 p=0.528	-50.60 p=0.036	-0.02 p=0.252	0.02 p=0.199	-0.00 p=0.899
E	+4	-12003.11 p=0.645	- 16428.13 p=0.460	-3.09 p=0.054	-1394.40 p=0.053	-1447.60 p=0.274	68.54 p=0.250	465.97 p=0.079	6735.60 p=0.381	0.60 p=0.727	-30.80 p=0.200	-0.05 p=0.237	0.01 p=0.597	0.04 p=0.434
E	+8	2563.00 p=0.250	4906.01 p=0.078	-2.49 p=0.005	-1276.80 p=0.013	-1425.20 p=0.034	30.79 p=0.118	208.69 p=0.284	122.00 p=0.474	0.20 p=0.876	-23.00 p=0.095	-0.06 p=0.031	0.03 p=0.078	0.03 p=0.154
A*	0	-1367.53 p=0.374	2032.19 p=0.165	-2.11 p=0.008	-1673.20 p=0.019	-689.20 p=0.139	12.52 p=0.566	72.28 p=0.832	-1120.00 p<0.001	-85.80 p=0.043	-36.60 p=0.055	-0.03 p=0.193	0.02 p=0.215	0.00 p=0.800
A*	+4	547.97 p=0.275	3852.82 p=0.006	-2.22 p=0.002	-1797.60 p=0.008	-468.40 p=0.147	12.82 p=0.149	70.54 p=0.762	-1120.00 p<0.001	-14.00 p=0.818	-26.80 p=0.051	-0.04 p=0.010	0.04 p=0.018	0.01 p=0.497
A*	+8	- 28828.33 p=0.364	- 25542.49 p=0.411	-3.09 p=0.005	-1372.00 p=0.044	-1489.20 p=0.115	15.68 p=0.616	682.77 p=0.252	-1120.00 p<0.001	-87.60 p=0.013	-12.80 p=0.555	-0.04 p=0.198	0.02 p=0.313	0.02 p=0.689
A**	0	6942.70 p=0.109	3436.51 p=0.004	-2.15 p=0.007	-1836.80 p=0.005	-158.40 p=0.625	48.10 p=0.227	270.40 p=0.335	5185.04 p=0.203	11.20 p=0.852	-29.20 p=0.029	-0.03 p=0.004	0.03 p=0.028	-0.00 p=0.991
A**	+4	5400.11 p=0.348	5439.67 p=0.018	-2.76 p=0.003	-1390.40 p=0.055	-1952.00 p=0.005	32.65 p=0.172	192.12 p=0.713	3080.84 p=0.398	-68.60 p=0.373	-30.60 p=0.163	-0.07 p<0.001	0.02 p=0.349	0.05 p=0.039
A**	+8	740.85 p=0.929	-3161.12 p=0.395	-1.75 p=0.018	-1528.80 p=0.024	-936.40 p=0.065	16.11 p=0.211	354.18 p=0.071	5998.64 p=0.390	-65.60 p=0.269	-17.20 p=0.256	-0.05 p=0.050	0.04 p=0.004	0.01 p=0.561
A***	0	1745.51 p=0.569	2520.36 p=0.078	-1.77 p=0.002	-1943.20 p<0.001	41.20 p=0.831	-3.03 p=0.813	-211.85 p=0.447	1343.80 p=0.527	29.00 p=0.589	-43.80 p=0.030	-0.02 p<0.001	0.04 p=0.002	-0.02 p=0.022
A***	+4	3309.01 p=0.499	1526.75 p=0.151	-2.56 p<0.001	-1565.60 p=0.061	-1045.20 p=0.203	8.77 p=0.646	277.95 p=0.570	4108.90 p=0.246	-71.80 p=0.249	-37.00 p=0.177	-0.04 p=0.095	0.03 p=0.063	0.01 p=0.649
A***	+8	6832.23 p=0.306	4720.81 p=0.002	-2.29 p<0.001	-1018.00 p=0.063	-1258.40 p=0.008	21.07 p<0.001	409.20 p=0.398	3959.85 p=0.424	5.00 p=0.940	-7.60 p=0.572	-0.08 p=0.011	0.04 p=0.008	0.04 p=0.028

Note: A*: Terminal Configuration A, under Force Majeure, delay penalty - 10%, A**: Terminal Configuration A, under Force Majeure, delay penalty - 50%, A***: Terminal Configuration A, under Force Majeure, extended delivery window +24h.

Table D.4: Equipment failure B: percentage changes.

Disruption		Planning Agent								Terminal Agent		Modal Split		
Terminal Config	Notification Delay	Overall	Request	Wait	Trans-shipment	(Un)loading	Emission	Storage	Delay	Reshuffles	Trans-shipments	Barge	Train	Truck
A	0	2.9% p=0.014	10.2% p=0.002	-11.9% p=0.002	-23.8% p<0.001	0.1% p=0.923	2.1% p=0.001	-2.8% p=0.445	22.9% p=0.267	2.0% p=0.238	-24.3% p=0.002	-3.68pp p=0.049	4.33pp p<0.001	-0.65pp p=0.559
A	+4	9.4% p=0.252	9.7% p=0.009	-13.3% p=0.003	-21.2% p=0.016	-3.6% p=0.013	2.2% p=0.106	3.2% p=0.601	490.7% p=0.365	-3.5% p=0.084	-20.0% p=0.024	-4.22pp p=0.026	3.22pp p=0.019	1.01pp p=0.378
A	+8	9.4% p=0.479	4.5% p=0.265	-13.4% p<0.001	-21.5% p=0.022	-4.3% p=0.004	-0.6% p=0.879	-2.4% p=0.725	702.5% p=0.378	-1.1% p=0.542	-21.7% p=0.048	-3.70pp p=0.063	4.07pp p=0.012	-0.38pp p=0.862
E	0	10.1% p=0.263	9.6% p=0.006	-8.6% p=0.021	-23.4% p=0.003	-1.5% p=0.469	3.5% p=0.077	-0.8% p=0.896	528.5% p=0.363	-2.0% p=0.528	-21.2% p=0.036	-2.04pp p=0.252	2.26pp p=0.199	-0.22pp p=0.899
E	+4	-16.4% p=0.645	-43.9% p=0.460	-18.5% p=0.054	-18.1% p=0.053	-6.7% p=0.274	14.0% p=0.250	10.4% p=0.079	601.4% p=0.381	1.7% p=0.727	-12.9% p=0.200	-4.71pp p=0.237	1.01pp p=0.597	3.70pp p=0.434
E	+8	3.5% p=0.250	13.1% p=0.078	-14.9% p=0.005	-16.6% p=0.013	-6.6% p=0.034	6.3% p=0.118	4.7% p=0.284	10.9% p=0.474	0.5% p=0.876	-9.6% p=0.095	-6.03pp p=0.031	3.10pp p=0.078	2.94pp p=0.154
A*	0	-1.9% p=0.374	5.4% p=0.165	-12.6% p=0.008	-21.7% p=0.019	-3.2% p=0.139	2.6% p=0.566	1.6% p=0.832	-100.0% p<0.001	-4.3% p=0.043	-15.4% p=0.055	-2.64pp p=0.193	2.23pp p=0.215	0.41pp p=0.800
A*	+4	0.8% p=0.275	10.3% p=0.006	-13.2% p=0.002	-23.3% p=0.008	-2.2% p=0.147	2.6% p=0.149	1.6% p=0.762	-100.0% p<0.001	-0.7% p=0.818	-11.3% p=0.051	-4.32pp p=0.010	3.71pp p=0.018	0.61pp p=0.497
A*	+8	-39.5% p=0.364	-68.2% p=0.411	-18.5% p=0.005	-17.8% p=0.044	-6.9% p=0.115	3.2% p=0.616	15.2% p=0.252	-100.0% p<0.001	-4.3% p=0.013	-5.4% p=0.555	-3.72pp p=0.198	2.10pp p=0.313	1.62pp p=0.689
A**	0	9.5% p=0.109	9.2% p=0.004	-12.8% p=0.007	-23.9% p=0.005	-0.7% p=0.625	9.9% p=0.227	6.0% p=0.335	463.0% p=0.203	0.6% p=0.852	-12.3% p=0.029	-2.83pp p=0.004	2.85pp p=0.028	-0.02pp p=0.991
A**	+4	7.4% p=0.348	14.5% p=0.018	-16.5% p=0.003	-18.1% p=0.055	-9.0% p=0.005	6.7% p=0.172	4.3% p=0.713	275.1% p=0.398	-3.6% p=0.373	-12.9% p=0.163	-6.89pp p<0.001	1.87pp p=0.349	5.02pp p=0.039
A**	+8	1.0% p=0.929	-8.4% p=0.395	-10.4% p=0.018	-19.9% p=0.024	-4.3% p=0.065	3.3% p=0.211	7.9% p=0.071	535.6% p=0.390	-3.3% p=0.269	-7.2% p=0.256	-5.45pp p=0.050	4.14pp p=0.004	1.32pp p=0.561
A***	0	2.4% p=0.569	6.7% p=0.078	-10.5% p=0.002	-25.2% p<0.001	0.2% p=0.831	-0.6% p=0.813	-4.7% p=0.447	120.0% p=0.527	1.5% p=0.589	-18.4% p=0.030	-2.24pp p<0.001	4.41pp p=0.002	-2.18pp p=0.022
A***	+4	4.5% p=0.499	4.1% p=0.151	-15.3% p<0.001	-20.3% p=0.061	-4.8% p=0.203	1.8% p=0.646	6.2% p=0.570	366.9% p=0.246	-3.6% p=0.249	-15.6% p=0.177	-4.21pp p=0.095	2.99pp p=0.063	1.22pp p=0.649
A***	+8	9.4% p=0.306	12.6% p=0.002	-13.6% p<0.001	-13.2% p=0.063	-5.8% p=0.008	4.3% p<0.001	9.1% p=0.398	353.6% p=0.424	0.3% p=0.940	-3.2% p=0.572	-7.60pp p=0.011	3.95pp p=0.008	3.65pp p=0.028

Note: A*: Terminal Configuration A, under Force Majeure, delay penalty - 10%, A**: Terminal Configuration A, under Force Majeure, delay penalty - 50%, A***: Terminal Configuration A, under Force Majeure, extended delivery window +24h.

Table D.5: Vehicle failure A: absolute values.

Disruption		Planning Agent								Terminal Agent		Modal Split		
Terminal Config	Notification Delay	Overall	Request	Wait	Trans-shipment	(Un)loading	Emission	Storage	Delay	Reshuffles	Trans-shipments	Barge	Train	Truck
A	0	7630.88 p=0.339	3495.17 p=0.012	-1.57 p=0.014	-1814.40 p=0.005	-746.40 p=0.136	10.46 p=0.201	-243.98 p=0.516	6931.60 p=0.377	-27.00 p=0.532	-54.40 p=0.011	-0.03 p=0.007	0.02 p=0.041	0.01 p=0.422
A	+4	6691.81 p=0.075	5159.45 p=0.021	-1.52 p=0.054	-1422.40 p=0.006	-184.80 p=0.169	19.81 p=0.022	439.68 p=0.077	2681.60 p=0.316	-31.80 p=0.617	-44.40 p=0.007	-0.04 p=0.012	0.04 p=0.015	-0.00 p=0.833
A	+8	11173.87 p=0.194	4621.66 p=0.024	-1.99 p=0.011	-1243.20 p=0.091	-1810.80 p=0.018	14.08 p=0.274	134.52 p=0.717	9459.60 p=0.229	-48.20 p=0.192	-26.40 p=0.322	-0.05 p=0.003	0.01 p=0.529	0.04 p=0.104
E	0	7187.70 p=0.348	2303.70 p=0.003	-1.15 p=0.003	-1282.40 p=0.003	-761.20 p=0.045	15.03 p=0.006	36.12 p=0.857	6877.60 p=0.376	0.80 p=0.495	-26.00 p=0.119	-0.01 p=0.339	-0.00 p=0.374	0.01 p=0.112
E	+4	9814.33 p=0.292	3705.84 p=0.037	-1.59 p=0.019	-1474.00 p=0.006	-914.40 p=0.019	16.32 p=0.047	144.56 p=0.720	8337.60 p=0.390	-1.60 p=0.438	-34.80 p=0.007	-0.03 p=0.022	0.03 p=0.085	0.00 p=0.557
E	+8	2569.69 p=0.380	4200.55 p=0.223	-1.45 p=0.137	-1405.60 p=0.003	-1086.00 p=0.065	22.51 p=0.290	138.08 p=0.623	701.60 p=0.398	-0.40 p=0.477	-31.80 p=0.017	-0.04 p=0.208	0.03 p=0.061	0.01 p=0.707
A*	0	-9190.01 p=0.353	-6156.67 p=0.492	-1.47 p=0.055	-1584.80 p=0.005	-233.20 p=0.499	25.64 p=0.236	-119.51 p=0.446	-1120.00 p<0.001	13.00 p=0.716	-25.20 p=0.136	-0.03 p=0.163	0.02 p=0.096	0.00 p=0.799
A*	+4	-1407.10 p=0.409	2053.63 p=0.031	-1.46 p=0.022	-1573.60 p=0.002	-583.60 p=0.338	-1.19 p=0.886	-180.88 p=0.588	-1120.00 p<0.001	-1.60 p=0.963	-18.80 p=0.169	-0.02 p=0.026	0.02 p=0.066	0.00 p=0.762
A*	+8	-471.67 p=0.867	2588.47 p=0.212	-1.28 p=0.022	-889.20 p=0.108	-1102.40 p=0.070	-0.43 p=0.977	53.16 p=0.903	-1120.00 p<0.001	-107.60 p=0.130	-2.60 p=0.857	-0.03 p=0.129	0.02 p=0.324	0.01 p=0.234
A**	0	2299.97 p=0.010	4482.01 p=0.002	-1.01 p=0.032	-1909.60 p<0.001	-268.40 p=0.358	17.67 p=0.013	-140.89 p=0.513	120.20 p=0.536	-9.80 p=0.819	-30.80 p=0.001	-0.04 p=0.016	0.04 p=0.002	0.00 p=0.751
A**	+4	2535.74 p=0.130	3960.97 p=0.045	-1.03 p=0.214	-991.20 p=0.025	-840.00 p=0.032	19.61 p=0.105	268.98 p=0.152	118.40 p=0.544	-36.60 p=0.277	2.00 p=0.815	-0.02 p=0.173	0.01 p=0.653	0.02 p=0.402
A**	+8	5143.32 p=0.619	- 32151.03 p=0.420	-1.96 p=0.028	-884.80 p=0.112	-1920.00 p=0.162	55.75 p=0.161	740.89 p=0.004	39304.47 p=0.272	-127.60 p=0.034	5.80 p=0.690	-0.06 p=0.112	-0.00 p=0.966	0.06 p=0.206
A***	0	- 53298.12 p=0.383	- 78697.06 p=0.378	-2.38 p=0.036	-1456.00 p=0.053	-1760.00 p=0.210	60.65 p=0.156	309.27 p=0.391	28247.40 p=0.332	-12.60 p=0.846	-0.20 p=0.995	-0.06 p=0.149	0.00 p=0.819	0.06 p=0.270
A***	+4	591.52 p=0.519	3596.33 p=0.010	-2.25 p=0.003	-1612.80 p=0.029	-807.60 p=0.096	13.95 p=0.047	19.89 p=0.942	-616.00 p=0.014	-111.80 p=0.217	-31.20 p=0.084	-0.02 p=0.161	0.02 p=0.347	0.00 p=0.796
A***	+8	9870.57 p=0.085	5495.71 p=0.025	-1.65 p=0.029	-312.40 p=0.424	-1364.00 p=0.040	28.39 p=0.046	563.09 p=0.031	5461.43 p=0.245	-40.60 p=0.451	20.40 p=0.174	-0.05 p=0.001	0.01 p=0.763	0.04 p=0.051

Note: A*: Terminal Configuration A, under Force Majeure, delay penalty - 10%, A**: Terminal Configuration A, under Force Majeure, delay penalty - 50%, A***: Terminal Configuration A, under Force Majeure, extended delivery window +24h.

Table D.6: Vehicle failure A: percentage changes.

Disruption		Planning Agent								Terminal Agent		Modal Split		
Terminal Config	Notification Delay	Overall	Request	Wait	Trans-shipment	(Un)loading	Emission	Storage	Delay	Reshuffles	Trans-shipments	Barge	Train	Truck
A	0	10.5% p=0.339	9.3% p=0.012	-9.3% p=0.014	-23.6% p=0.005	-3.4% p=0.136	2.1% p=0.201	-5.4% p=0.516	618.9% p=0.377	-1.2% p=0.532	-22.9% p=0.011	-2.82pp p=0.007	1.93pp p=0.041	0.89pp p=0.422
A	+4	9.2% p=0.075	13.8% p=0.021	-9.1% p=0.054	-18.5% p=0.006	-0.9% p=0.169	4.1% p=0.022	9.8% p=0.077	239.4% p=0.316	-1.5% p=0.617	-18.7% p=0.007	-3.77pp p=0.012	3.90pp p=0.015	-0.13pp p=0.833
A	+8	15.3% p=0.194	12.3% p=0.024	-11.9% p=0.011	-16.1% p=0.091	-8.3% p=0.018	2.9% p=0.274	3.0% p=0.717	844.6% p=0.229	-2.3% p=0.192	-11.1% p=0.322	-5.38pp p=0.003	1.41pp p=0.529	3.97pp p=0.104
E	0	9.9% p=0.348	6.2% p=0.003	-6.9% p=0.003	-16.7% p=0.003	-3.5% p=0.045	3.1% p=0.006	0.8% p=0.857	614.1% p=0.376	2.4% p=0.495	-10.9% p=0.119	-0.82pp p=0.339	-0.46pp p=0.374	1.28pp p=0.112
E	+4	13.5% p=0.292	9.9% p=0.037	-9.5% p=0.019	-19.1% p=0.006	-4.2% p=0.019	3.3% p=0.047	3.2% p=0.720	744.4% p=0.390	-4.1% p=0.438	-14.6% p=0.007	-2.99pp p=0.022	2.54pp p=0.085	0.46pp p=0.557
E	+8	3.5% p=0.380	11.2% p=0.223	-8.7% p=0.137	-18.3% p=0.003	-5.0% p=0.065	4.6% p=0.290	3.1% p=0.623	62.6% p=0.398	-1.1% p=0.477	-13.3% p=0.017	-4.11pp p=0.208	3.10pp p=0.061	1.01pp p=0.707
A*	0	-12.6% p=0.353	-16.4% p=0.492	-8.8% p=0.055	-20.6% p=0.005	-1.1% p=0.499	5.3% p=0.236	-2.7% p=0.446	-100.0% p<0.001	0.7% p=0.716	-10.6% p=0.136	-2.55pp p=0.163	2.31pp p=0.096	0.25pp p=0.799
A*	+4	-1.9% p=0.409	5.5% p=0.031	-8.7% p=0.022	-20.4% p=0.002	-2.7% p=0.338	-0.2% p=0.886	-4.0% p=0.588	-100.0% p<0.001	-0.1% p=0.963	-7.9% p=0.169	-2.43pp p=0.026	2.09pp p=0.066	0.35pp p=0.762
A*	+8	-0.6% p=0.867	6.9% p=0.212	-7.6% p=0.022	-11.5% p=0.108	-5.1% p=0.070	-0.1% p=0.977	1.2% p=0.903	-100.0% p<0.001	-5.5% p=0.130	-1.1% p=0.857	-2.82pp p=0.129	1.59pp p=0.324	1.23pp p=0.234
A**	0	3.2% p=0.010	12.0% p=0.002	-6.0% p=0.032	-24.8% p<0.001	-1.2% p=0.358	3.6% p=0.013	-3.1% p=0.513	10.7% p=0.536	-0.5% p=0.819	-13.0% p=0.001	-3.90pp p=0.016	3.53pp p=0.002	0.37pp p=0.751
A**	+4	3.5% p=0.130	10.6% p=0.045	-6.1% p=0.214	-12.9% p=0.025	-3.9% p=0.032	4.0% p=0.105	6.0% p=0.152	10.6% p=0.544	-1.9% p=0.277	0.8% p=0.815	-2.30pp p=0.173	0.64pp p=0.653	1.66pp p=0.402
A**	+8	7.0% p=0.619	-85.9% p=0.420	-11.7% p=0.028	-11.5% p=0.112	-8.8% p=0.162	11.4% p=0.161	16.5% p=0.004	3509.3% p=0.272	-6.3% p=0.034	2.4% p=0.690	-5.78pp p=0.112	-0.12pp p=0.966	5.91pp p=0.206
A***	0	-73.0% p=0.383	-210.2% p=0.378	-14.2% p=0.036	-18.9% p=0.053	-8.1% p=0.210	12.4% p=0.156	6.9% p=0.391	2522.1% p=0.332	-0.6% p=0.846	-0.1% p=0.995	-5.99pp p=0.149	0.37pp p=0.819	5.62pp p=0.270
A***	+4	0.8% p=0.519	9.6% p=0.010	-13.4% p=0.003	-20.9% p=0.029	-3.7% p=0.096	2.9% p=0.047	0.4% p=0.942	-55.0% p=0.014	-5.6% p=0.217	-13.1% p=0.084	-2.12pp p=0.161	1.80pp p=0.347	0.32pp p=0.796
A***	+8	13.5% p=0.085	14.7% p=0.025	-9.9% p=0.029	-4.1% p=0.424	-6.3% p=0.040	5.8% p=0.046	12.6% p=0.031	487.6% p=0.245	-2.0% p=0.451	8.6% p=0.174	-4.83pp p=0.001	0.60pp p=0.763	4.23pp p=0.051

Note: A*: Terminal Configuration A, under Force Majeure, delay penalty - 10%, A**: Terminal Configuration A, under Force Majeure, delay penalty - 50%, A***: Terminal Configuration A, under Force Majeure, extended delivery window +24h.

Table D.7: Vehicle failure B: absolute values.

Disruption		Planning Agent								Terminal Agent		Modal Split		
Terminal Config	Notification Delay	Overall	Request	Wait	Trans-shipment	(Un)loading	Emission	Storage	Delay	Reshuffles	Trans-shipments	Barge	Train	Truck
A	0	3563.21 p=0.355	4581.48 p=0.029	-2.44 p=0.009	-2223.20 p=0.008	-1322.80 p=0.092	22.59 p=0.248	11.98 p=0.970	2495.60 p=0.355	-24.00 p=0.418	-61.60 p=0.025	-0.07 p=0.009	0.04 p=0.072	0.03 p=0.225
A	+4	6575.32 p=0.061	7958.48 p=0.005	-2.23 p<0.001	-1517.60 p=0.136	-1298.00 p=0.057	49.95 p=0.023	597.31 p=0.058	787.40 p=0.426	-47.40 p=0.418	-32.40 p=0.398	-0.05 p=0.028	0.01 p=0.523	0.04 p=0.114
A	+8	21630.70 p=0.047	11800.77 p=0.007	-2.07 p=0.024	-1271.20 p=0.122	-1814.80 p=0.009	64.94 p=0.003	906.86 p=0.004	11946.20 p=0.237	-52.40 p=0.097	-23.20 p=0.348	-0.09 p=0.010	0.04 p=0.151	0.05 p=0.011
E	0	3581.78 p=0.011	5501.19 p=0.002	-1.89 p<0.001	-1635.20 p=0.003	-1144.00 p=0.020	34.11 p=0.002	134.77 p=0.513	692.80 p=0.150	4.80 p=0.111	-29.20 p=0.013	-0.04 p=0.029	0.02 p=0.395	0.03 p=0.040
E	+4	9574.67 p=0.219	4761.19 p=0.039	-1.57 p=0.002	-1254.40 p=0.007	-1249.20 p=0.011	25.23 p=0.030	85.82 p=0.807	7207.60 p=0.381	6.40 p=0.304	-17.20 p=0.216	-0.05 p=0.016	0.03 p=0.225	0.02 p=0.176
E	+8	9848.25 p=0.007	10707.47 p=0.005	-2.30 p<0.001	-1562.40 p=0.002	-1738.00 p=0.015	63.90 p=0.003	796.78 p=0.006	1582.80 p=0.178	3.60 p=0.276	-30.20 p=0.074	-0.07 p=0.005	0.02 p=0.456	0.05 p=0.027
A*	0	-390.74 p=0.813	3899.25 p=0.008	-2.52 p<0.001	-1635.20 p=0.009	-1529.60 p=0.013	17.51 p=0.108	-20.18 p=0.961	-1120.00 p<0.001	-48.60 p=0.404	-21.00 p=0.255	-0.03 p=0.159	-0.01 p=0.514	0.04 p=0.003
A*	+4	-9051.72 p=0.415	-6194.64 p=0.552	-2.49 p=0.035	-1444.80 p=0.047	-1855.20 p=0.030	42.86 p=0.240	492.94 p=0.303	-90.40 p=0.895	-93.80 p=0.065	-13.40 p=0.560	-0.03 p=0.146	-0.01 p=0.257	0.05 p=0.106
A*	+8	2519.90 p=0.119	5549.54 p=0.024	-1.94 p=0.006	-655.20 p=0.204	-1738.00 p=0.030	29.70 p=0.062	455.80 p=0.130	-1120.00 p<0.001	-43.40 p=0.293	14.00 p=0.386	-0.05 p=0.004	-0.00 p=0.836	0.06 p=0.044
A**	0	7872.56 p=0.082	5604.53 p=0.066	-2.23 p=0.030	-1803.20 p=0.015	-1408.00 p=0.110	60.80 p=0.009	247.91 p=0.434	5172.75 p=0.339	-85.20 p=0.208	-26.20 p=0.219	-0.05 p=0.045	0.01 p=0.790	0.04 p=0.120
A**	+4	-5234.08 p=0.821	- 13513.79 p=0.551	-2.90 p=0.003	-1495.20 p=0.005	-2204.40 p=0.026	64.01 p=0.039	209.95 p=0.348	11708.24 p=0.199	-16.80 p=0.645	-11.60 p=0.369	-0.08 p=0.002	0.01 p=0.713	0.07 p=0.042
A**	+8	4423.93 p=0.439	5961.92 p=0.278	-3.72 p=0.001	-974.40 p=0.253	-2541.20 p=0.003	34.21 p=0.247	469.72 p=0.111	1477.40 p=0.170	-205.60 p=0.061	2.60 p=0.929	-0.05 p=0.058	-0.01 p=0.587	0.07 p=0.031
A***	0	5367.66 p=0.235	7620.58 p=0.031	-2.57 p=0.010	-1836.80 p=0.017	-2154.40 p=0.053	51.05 p=0.068	-313.00 p=0.282	2002.80 p=0.468	50.40 p=0.556	-24.60 p=0.260	-0.06 p=0.017	0.00 p=0.840	0.06 p=0.066
A***	+4	2261.99 p=0.545	7258.63 p=0.059	-3.32 p<0.001	-1601.60 p=0.048	-3034.40 p=0.002	55.03 p=0.014	28.64 p=0.934	-441.00 p=0.013	-20.60 p=0.647	-19.20 p=0.369	-0.08 p=0.010	-0.01 p=0.538	0.09 p<0.001
A***	+8	8114.51 p=0.192	7953.45 p=0.006	-2.65 p=0.017	-1114.40 p=0.017	-2994.40 p=0.009	45.13 p=0.019	336.97 p=0.300	3890.40 p=0.430	-127.20 p=0.022	-3.60 p=0.792	-0.08 p=0.018	-0.01 p=0.605	0.08 p=0.004

Note: A*: Terminal Configuration A, under Force Majeure, delay penalty - 10%, A**: Terminal Configuration A, under Force Majeure, delay penalty - 50%, A***: Terminal Configuration A, under Force Majeure, extended delivery window +24h.

Table D.8: Vehicle failure B: percentage changes.

Disruption		Planning Agent								Terminal Agent		Modal Split		
Terminal Config	Notification Delay	Overall	Request	Wait	Trans-shipment	(Un)loading	Emission	Storage	Delay	Reshuffles	Trans-shipments	Barge	Train	Truck
A	0	4.9% p=0.355	12.2% p=0.029	-14.6% p=0.009	-28.9% p=0.008	-6.1% p=0.092	4.6% p=0.248	0.3% p=0.970	222.8% p=0.355	-1.1% p=0.418	-25.9% p=0.025	-6.63pp p=0.009	3.73pp p=0.072	2.90pp p=0.225
A	+4	9.0% p=0.061	21.3% p=0.005	-13.3% p<0.001	-19.7% p=0.136	-6.0% p=0.057	10.2% p=0.023	13.3% p=0.058	70.3% p=0.426	-2.1% p=0.418	-13.6% p=0.398	-5.03pp p=0.028	1.04pp p=0.523	3.99pp p=0.114
A	+8	29.6% p=0.047	31.5% p=0.007	-12.3% p=0.024	-16.5% p=0.122	-8.4% p=0.009	13.3% p=0.003	20.2% p=0.004	1066.6% p=0.237	-2.4% p=0.097	-9.8% p=0.348	-9.26pp p=0.010	3.87pp p=0.151	5.38pp p=0.011
E	0	4.9% p=0.011	14.7% p=0.002	-11.3% p<0.001	-21.2% p=0.003	-5.3% p=0.020	7.0% p=0.002	3.0% p=0.513	61.9% p=0.150	13.4% p=0.111	-12.2% p=0.013	-4.41pp p=0.029	1.78pp p=0.395	2.63pp p=0.040
E	+4	13.1% p=0.219	12.7% p=0.039	-9.4% p=0.002	-16.3% p=0.007	-5.8% p=0.011	5.2% p=0.030	1.9% p=0.807	643.5% p=0.381	17.0% p=0.304	-7.2% p=0.216	-4.89pp p=0.016	2.59pp p=0.225	2.30pp p=0.176
E	+8	13.5% p=0.007	28.6% p=0.005	-13.7% p<0.001	-20.3% p=0.002	-8.0% p=0.015	13.1% p=0.003	17.8% p=0.006	141.3% p=0.178	9.7% p=0.276	-12.6% p=0.074	-6.75pp p=0.005	2.03pp p=0.456	4.72pp p=0.027
A*	0	-0.5% p=0.813	10.4% p=0.008	-15.1% p<0.001	-21.2% p=0.009	-7.0% p=0.013	3.6% p=0.108	-0.5% p=0.961	-100.0% p<0.001	-2.5% p=0.404	-8.8% p=0.255	-2.72pp p=0.159	-0.98pp p=0.514	3.69pp p=0.003
A*	+4	-12.4% p=0.415	-16.5% p=0.552	-14.9% p=0.035	-18.8% p=0.047	-8.5% p=0.030	8.8% p=0.240	11.0% p=0.303	-8.1% p=0.895	-4.6% p=0.065	-5.6% p=0.560	-3.37pp p=0.146	-1.40pp p=0.257	4.77pp p=0.106
A*	+8	3.5% p=0.119	14.8% p=0.024	-11.6% p=0.006	-8.5% p=0.204	-8.0% p=0.030	6.1% p=0.062	10.2% p=0.130	-100.0% p<0.001	-2.2% p=0.293	5.9% p=0.386	-5.23pp p=0.004	-0.31pp p=0.836	5.54pp p=0.044
A**	0	10.8% p=0.082	15.0% p=0.066	-13.3% p=0.030	-23.4% p=0.015	-6.5% p=0.110	12.5% p=0.009	5.5% p=0.434	461.9% p=0.339	-4.4% p=0.208	-11.0% p=0.219	-5.37pp p=0.045	0.99pp p=0.790	4.38pp p=0.120
A**	+4	-7.2% p=0.821	-36.1% p=0.551	-17.3% p=0.003	-19.4% p=0.005	-10.2% p=0.026	13.1% p=0.039	4.7% p=0.348	1045.4% p=0.199	-0.8% p=0.645	-4.9% p=0.369	-7.83pp p=0.002	0.65pp p=0.713	7.18pp p=0.042
A**	+8	6.1% p=0.439	15.9% p=0.278	-22.2% p=0.001	-12.7% p=0.253	-11.7% p=0.003	7.0% p=0.247	10.5% p=0.111	131.9% p=0.170	-10.5% p=0.061	1.1% p=0.929	-5.49pp p=0.058	-1.01pp p=0.587	6.50pp p=0.031
A***	0	7.4% p=0.235	20.4% p=0.031	-15.3% p=0.010	-23.9% p=0.017	-9.9% p=0.053	10.5% p=0.068	-7.0% p=0.282	178.8% p=0.468	2.6% p=0.556	-10.4% p=0.260	-6.43pp p=0.017	0.45pp p=0.840	5.98pp p=0.066
A***	+4	3.1% p=0.545	19.4% p=0.059	-19.8% p<0.001	-20.8% p=0.048	-14.0% p=0.002	11.3% p=0.014	0.6% p=0.934	-39.4% p=0.013	-1.0% p=0.647	-8.1% p=0.369	-8.18pp p=0.010	-0.90pp p=0.538	9.08pp p<0.001
A***	+8	11.1% p=0.192	21.2% p=0.006	-15.8% p=0.017	-14.5% p=0.017	-13.8% p=0.009	9.2% p=0.019	7.5% p=0.300	347.4% p=0.430	-6.3% p=0.022	-1.5% p=0.792	-7.63pp p=0.018	-0.70pp p=0.605	8.33pp p=0.004

Note: A*: Terminal Configuration A, under Force Majeure, delay penalty - 10%, A**: Terminal Configuration A, under Force Majeure, delay penalty - 50%, A***: Terminal Configuration A, under Force Majeure, extended delivery window +24h.

Table D.9: Vehicle failure C: absolute values.

Disruption		Planning Agent								Terminal Agent		Modal Split		
Terminal Config	Notification Delay	Overall	Request	Wait	Trans-shipment	(Un)loading	Emission	Storage	Delay	Reshuffles	Trans-shipments	Barge	Train	Truck
A	0	13277.54 p=0.114	11719.42 p<0.001	-2.83 p<0.001	-2469.60 p=0.006	-1685.20 p=0.005	63.43 p<0.001	-41.27 p=0.879	5693.60 p=0.383	-6.60 p=0.880	-63.00 p=0.024	-0.11 p=0.001	0.06 p=0.041	0.05 p=0.012
A	+4	4611.23 p=0.095	8889.66 p=0.004	-3.11 p=0.004	-1737.60 p=0.060	-2435.60 p<0.001	40.59 p=0.026	-88.71 p=0.828	-54.00 p=0.110	-91.20 p=0.278	-38.20 p=0.196	-0.10 p=0.003	0.04 p=0.124	0.06 p=0.002
A	+8	6372.93 p=0.086	9175.31 p=0.015	-3.98 p<0.001	-1457.60 p=0.045	-2990.00 p=0.003	44.88 p=0.065	212.72 p=0.482	1391.60 p=0.145	-129.00 p=0.155	-21.60 p=0.305	-0.12 p=0.008	0.04 p=0.132	0.08 p<0.001
E	0	12531.39 p=0.019	12303.17 p=0.014	-2.48 p=0.021	-1523.20 p=0.017	-2085.60 p=0.048	64.39 p=0.062	-132.49 p=0.550	3907.60 p=0.334	6.60 p=0.214	-23.00 p=0.275	-0.12 p=0.011	0.06 p=0.055	0.06 p=0.104
E	+4	11143.12 p=0.032	10661.57 p=0.006	-2.47 p=0.027	-1131.20 p=0.082	-2410.80 p=0.030	47.60 p=0.039	450.82 p=0.251	3527.60 p=0.390	3.40 p=0.473	-10.60 p=0.520	-0.12 p=0.017	0.05 p=0.011	0.06 p=0.106
E	+8	24347.79 p=0.134	14730.86 p=0.033	-2.71 p=0.011	-2122.40 p=0.010	-2221.60 p=0.023	75.14 p=0.040	378.89 p=0.541	13509.60 p=0.261	1.20 p=0.208	-49.00 p=0.026	-0.10 p=0.015	0.05 p=0.005	0.06 p=0.101
A*	0	-7345.91 p=0.528	-1059.48 p=0.924	-4.23 p=0.002	-1286.80 p=0.003	-3872.00 p=0.002	80.52 p=0.031	-83.93 p=0.704	-1120.00 p<0.001	-41.60 p=0.223	-18.80 p=0.104	-0.13 p=0.004	-0.00 p=0.901	0.13 p=0.002
A*	+4	- 13178.64 p=0.454	-6635.85 p=0.674	-3.79 p=0.056	-2038.40 p=0.002	-3852.40 p=0.046	107.24 p=0.219	364.56 p=0.519	-1120.00 p<0.001	8.60 p=0.865	-44.40 p=0.065	-0.13 p=0.055	0.02 p=0.396	0.11 p=0.116
A*	+8	5139.85 p=0.259	9530.15 p=0.058	-3.06 p=0.013	-687.60 p=0.176	-3196.80 p=0.004	43.04 p=0.172	574.12 p=0.161	-1120.00 p<0.001	-131.20 p=0.129	8.60 p=0.630	-0.08 p=0.021	-0.01 p=0.761	0.09 p=0.008
A**	0	4740.42 p=0.099	8435.41 p=0.001	-2.90 p=0.004	-1870.40 p=0.029	-2559.20 p<0.001	40.25 p=0.011	142.89 p=0.690	554.36 p=0.495	-59.40 p=0.230	-29.40 p=0.272	-0.09 p=0.016	0.02 p=0.472	0.07 p<0.001
A**	+4	3995.71 p=0.178	8793.59 p=0.005	-3.92 p<0.001	-1736.00 p=0.039	-2805.60 p=0.011	48.75 p=0.002	-86.52 p=0.844	-214.60 p=0.466	-73.20 p=0.147	-24.60 p=0.313	-0.11 p<0.001	0.02 p=0.296	0.08 p=0.010
A**	+8	13283.71 p=0.060	9502.69 p=0.010	-2.65 p=0.028	-1517.60 p=0.010	-2256.80 p=0.029	51.37 p=0.048	613.54 p=0.158	6893.15 p=0.310	-17.80 p=0.658	-12.40 p=0.324	-0.08 p=0.092	0.02 p=0.527	0.07 p=0.075
A***	0	3658.70 p=0.408	9005.37 p=0.068	-2.66 p=0.001	-1976.80 p=0.011	-2458.00 p=0.026	45.89 p=0.029	-236.10 p=0.305	-719.00 p=0.016	-22.20 p=0.703	-34.20 p=0.073	-0.12 p=0.002	0.05 p=0.045	0.07 p=0.027
A***	+4	6501.43 p=0.119	10729.87 p=0.018	-3.37 p=0.012	-1321.60 p=0.151	-3720.80 p=0.007	55.66 p=0.056	-264.14 p=0.533	1025.80 p=0.571	-123.60 p=0.138	-14.20 p=0.692	-0.10 p=0.031	-0.02 p=0.111	0.11 p=0.022
A***	+8	3920.45 p=0.155	9041.44 p=0.006	-3.37 p=0.007	-1702.40 p=0.042	-3377.60 p=0.014	56.71 p=0.018	148.67 p=0.636	-243.00 p=0.590	-71.00 p=0.259	-7.80 p=0.759	-0.12 p=0.006	0.01 p=0.298	0.10 p=0.023

Note: A*: Terminal Configuration A, under Force Majeure, delay penalty - 10%, A**: Terminal Configuration A, under Force Majeure, delay penalty - 50%, A***: Terminal Configuration A, under Force Majeure, extended delivery window +24h.

Table D.10: Vehicle failure C: percentage changes.

Disruption		Planning Agent								Terminal Agent		Modal Split		
Terminal Config	Notification Delay	Overall	Request	Wait	Trans-shipment	(Un)loading	Emission	Storage	Delay	Reshuffles	Trans-shipments	Barge	Train	Truck
A	0	18.2% p=0.114	31.3% p<0.001	-16.9% p<0.001	-32.1% p=0.006	-7.8% p=0.005	13.0% p<0.001	-0.9% p=0.879	508.4% p=0.383	-0.3% p=0.880	-26.5% p=0.024	-11.05pp p=0.001	5.70pp p=0.041	5.36pp p=0.012
A	+4	6.3% p=0.095	23.7% p=0.004	-18.5% p=0.004	-22.6% p=0.060	-11.2% p<0.001	8.3% p=0.026	-2.0% p=0.828	-4.8% p=0.110	-4.2% p=0.278	-16.1% p=0.196	-10.05pp p=0.003	3.91pp p=0.124	6.14pp p=0.002
A	+8	8.7% p=0.086	24.5% p=0.015	-23.8% p<0.001	-18.9% p=0.045	-13.8% p=0.003	9.2% p=0.065	4.7% p=0.482	124.2% p=0.145	-5.8% p=0.155	-9.1% p=0.305	-12.35pp p=0.008	4.20pp p=0.132	8.15pp p<0.001
E	0	17.2% p=0.019	32.9% p=0.014	-14.8% p=0.021	-19.8% p=0.017	-9.6% p=0.048	13.2% p=0.062	-3.0% p=0.550	348.9% p=0.334	17.2% p=0.214	-9.6% p=0.275	-11.78pp p=0.011	5.84pp p=0.055	5.94pp p=0.104
E	+4	15.3% p=0.032	28.5% p=0.006	-14.8% p=0.027	-14.7% p=0.082	-11.1% p=0.030	9.8% p=0.039	10.1% p=0.251	315.0% p=0.390	8.9% p=0.473	-4.4% p=0.520	-11.62pp p=0.017	5.22pp p=0.011	6.39pp p=0.106
E	+8	33.4% p=0.134	39.3% p=0.033	-16.2% p=0.011	-27.6% p=0.010	-10.2% p=0.023	15.4% p=0.040	8.5% p=0.541	1206.2% p=0.261	3.3% p=0.208	-20.5% p=0.026	-10.29pp p=0.015	4.54pp p=0.005	5.76pp p=0.101
A*	0	-10.1% p=0.528	-2.8% p=0.924	-25.2% p=0.002	-16.7% p=0.003	-17.8% p=0.002	16.5% p=0.031	-1.9% p=0.704	-100.0% p<0.001	-2.1% p=0.223	-7.9% p=0.104	-12.65pp p=0.004	-0.40pp p=0.901	13.05pp p=0.002
A*	+4	-18.1% p=0.454	-17.7% p=0.674	-22.6% p=0.056	-26.5% p=0.002	-17.7% p=0.046	22.0% p=0.219	8.1% p=0.519	-100.0% p<0.001	0.4% p=0.865	-18.7% p=0.065	-12.70pp p=0.055	1.63pp p=0.396	11.07pp p=0.116
A*	+8	7.0% p=0.259	25.5% p=0.058	-18.3% p=0.013	-8.9% p=0.176	-14.7% p=0.004	8.8% p=0.172	12.8% p=0.161	-100.0% p<0.001	-6.7% p=0.129	3.6% p=0.630	-8.32pp p=0.021	-0.63pp p=0.761	8.95pp p=0.008
A**	0	6.5% p=0.099	22.5% p=0.001	-17.3% p=0.004	-24.3% p=0.029	-11.8% p<0.001	8.2% p=0.011	3.2% p=0.690	49.5% p=0.495	-3.0% p=0.230	-12.4% p=0.272	-9.11pp p=0.016	1.78pp p=0.472	7.32pp p<0.001
A**	+4	5.5% p=0.178	23.5% p=0.005	-23.4% p<0.001	-22.5% p=0.039	-12.9% p=0.011	10.0% p=0.002	-1.9% p=0.844	-19.2% p=0.466	-3.7% p=0.147	-10.4% p=0.313	-10.53pp p<0.001	2.25pp p=0.296	8.29pp p=0.010
A**	+8	18.2% p=0.060	25.4% p=0.010	-15.8% p=0.028	-19.7% p=0.010	-10.4% p=0.029	10.5% p=0.048	13.7% p=0.158	615.5% p=0.310	-0.9% p=0.658	-5.2% p=0.324	-8.37pp p=0.092	1.69pp p=0.527	6.69pp p=0.075
A***	0	5.0% p=0.408	24.0% p=0.068	-15.9% p=0.001	-25.7% p=0.011	-11.3% p=0.026	9.4% p=0.029	-5.3% p=0.305	-64.2% p=0.016	-1.1% p=0.703	-14.4% p=0.073	-11.90pp p=0.002	4.86pp p=0.045	7.05pp p=0.027
A***	+4	8.9% p=0.119	28.7% p=0.018	-20.1% p=0.012	-17.2% p=0.151	-17.1% p=0.007	11.4% p=0.056	-5.9% p=0.533	91.6% p=0.571	-6.2% p=0.138	-6.0% p=0.692	-9.56pp p=0.031	-1.81pp p=0.111	11.37pp p=0.022
A***	+8	5.4% p=0.155	24.1% p=0.006	-20.1% p=0.007	-22.1% p=0.042	-15.6% p=0.014	11.6% p=0.018	3.3% p=0.636	-21.7% p=0.590	-3.6% p=0.259	-3.3% p=0.759	-11.69pp p=0.006	1.41pp p=0.298	10.28pp p=0.023

Note: A*: Terminal Configuration A, under Force Majeure, delay penalty - 10%, A**: Terminal Configuration A, under Force Majeure, delay penalty - 50%, A***: Terminal Configuration A, under Force Majeure, extended delivery window +24h.