Design & Simulation of an Integrated **Automated Maglev System** to Overcome Transportation Challenges between Inland and Seaport Terminals

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Design & Simulation of an Integrated Automated Maglev System to Overcome Transportation Challenges between Inland and Seaport Terminals

by

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Preface

Dear reader,

You are about to embark on the journey detailed in my bachelor thesis, ”Design & Simulation of an Integrated Automated Maglev System to Overcome Transportation Challenges between Inland and Seaport Terminals.”

This adventure began in July 2024 with a transformative visit to Max Bögl’s headquarters in Sengenthal, Bavaria, Germany. I am deeply grateful to the entire TSB team for their warm welcome and unwavering support, especially to my supervisor Felix Niebler, who guided me expertly through all complexities and introduced me to amazing TSB system. I also want to thank Hans de Koning and Andreas Rau for enabling such an exciting project. The future of TSB holds exciting prospects, and I eagerly anticipate its evolution!

My time at TU Delft has been profoundly enriching, filled with learning, growth, and numerous memorable experiences. I truly appreciate the feedback, comprehension, support and guidance that my supervisors Mahnam, Stefano and Lóri gave me during all these months. I am immensely proud to have studied at TU Delft, an experience that profoundly enriched me with new knowledge and experiences, while also deepening my passion for logistics and supply chain. The emotional rollercoaster of the thesis period, with its ups and downs, showed me once again that all the effort and hard work pays off.

I extend heartfelt thanks to my amazing housemates, who have been my family during all this time, together with the rest of my close friends in the Netherlands. Also, to all my dear friends back in Valladolid—especially my best friend Danielso—who, though far in distance, were always close at heart. To Lateesha, my unconditional, always my main support. And to my beautiful family and beloved grandfather, who have been my foundation and inspiration, this achievement is as much yours as it is mine, thank you for giving me this opportunity. Thank you for your love, sacrifice, and belief in my dreams.

I wish you an enjoyable reading.

Sincerely, Ernesto Sanz González
Delft, April 2024

Abstract

Port systems face numerous challenges, including limited storage capacity at terminal yards, congestion in road port access due to overwhelmed infrastructure, and inefficient inter-terminal transportation. Close dry ports, situated between 10-40 km from the port, offer a potential solution, but lack flexible and reliable transport connections that efficiently handle transportation without adding extra handling moves. Recent technological advances in rail systems, particularly fully automated magnetic levitation (maglev) cargo shuttles, provide promising solutions for connecting dry ports with seaport terminals.

This research explores the integration of maglev technology into port logistics, focusing on connecting a dry port terminal to seaport terminals, with a direct connection to the berth. Using the Transport System Bögl (TSB) Cargo system as a reference, five different designs were developed for integration. These designs required a redesign of the dry port and terminal yard, as well as the design of the system's berth connection and connections between all terminals.

Simulation modeling using Siemens Tecnomatix Plant Simulation software evaluated the performance of these designs under various scenarios based on Port of Hamburg demand input data. Results showed that all designs improved median berth times compared to the German benchmark of 18.96 hours, with Design 5 demonstrating the best performance together with Design 2.

Recommendations include continued collaboration with port authorities through simulation case studies, serving as proof of performance for potential integration projects, and exploration of collaboration opportunities with smaller scale ports facing space availability and road access issues. Further research should expand the model to accommodate new export container loading requirements and include all terminals, while studying new algorithms to balance the volumes and requests of all three terminals. This research demonstrates the feasibility of integrating maglev systems into port logistics, challenging the 'status quo' and opening up new possibilities for improving port operations. Through a systematic approach, this study offers valuable insights for the integration of maglev technology into port logistics, paving the way for future advancements in the field.

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Introduction

1.1. Research context & problem

In the context of rapidly changing global trade dynamics, the movement of goods has surged due to the growth in population, economic activities, and international commerce (Tavasszy and de Jong, 2014). However, this growth has triggered challenges for deep sea container ports worldwide, exposing the limitations of these ones, grappling with spatial constraints impeding their development along coastal areas (Cullinane and Wilmsmeier, 2011). The surge in trade operations has not only burdened port infrastructure but has also intensified the flow of trucks and vehicles moving to and from these ports. This increase in vehicular movement has led to severe traffic congestion, environmental pollution, and adversely impacted urban quality of life. Apart from these issues, logistical inefficiencies have driven up costs, prolonged wait times, and raised safety concerns.

In response to adverse effects of increasing container volumes at sea ports, a potential solution has emerged: the strategic deployment of dry ports situated away from the primary port area. As defined by Roso and Leveque, 2002, a dry port is an inland intermodal terminal directly connected to seaport(s) with high capacity transport mean(s), where customers can leave or pick up their containers as if directly to a seaport. Based on the function and location respect to the seaport, they can be categorized as distant, midrange and close dry ports (Roso et al., 2009), and this study will be focused on the latter one. Close dry ports are situated at the rim of the city area, in a location with good road access and high infrastructure capacity (see Figure 1.1). The main purpose of these terminals is to increase storage space for containers and streamlining truck access, alleviating the traffic congestion and pollution within cities, benefiting truckers as well as area residents. Furthermore, apart from storage they can also provide other functions such as customs clearance, consolidation, or maintenance and repair of containers, facilitating smoother port operations at the seaport. From the close dry port there is generally a rail shuttle service in place for moving the containers to the seaport terminals, however this generally leads to the need of intermediate storage at the yard. This storage transition also empowers seaport terminals to prioritize enhancements in other domains such as rail freight handling, a sector with significant growth potential (European Union Agency for Railways, 2022). Moreover, in cities not allowing long or polluting road vehicles, the usage of the close dry port is an alternative to changing to smaller trucks or non-polluting ones (Roso et al., 2009).

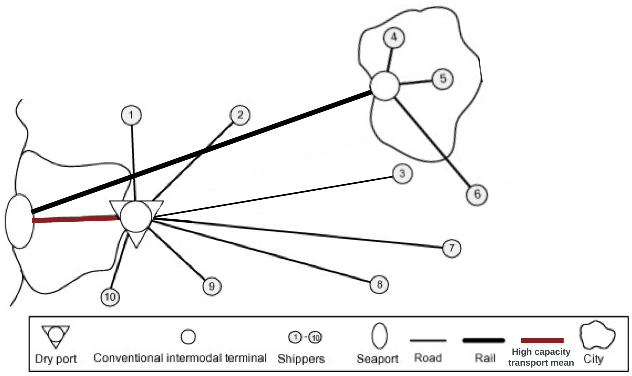

Figure 1.1: A seaport with a close dry port. (Adapted from Roso et al., 2009).

However, despite the potential offered by dry ports, they lack a flexible, reactive, and reliable transport solution for establishing a seamless connection between these auxiliary terminals and the main port. This absence of direct linkage without the need for intermediate storage significantly decreases the efficiency of operations. At the same time, the intra-port movement of containers between diverse terminals poses its own set of complications. The complexities of this process, which include expenses, time consumption, and unpredictability, echo as concerns for both shipowners and shippers.

New technological advances in rail systems provide new ways of connecting dry ports with sea ports. In particular, fully automated magnetic levitation (maglev) cargo shuttles have been recently developed for container transportation (Siegmund, 2021). Magnetic levitation, also known as maglev, is a type of transportation system that uses magnetic fields to suspend and propel a train above its tracks. Instead of relying on wheels or traditional tracks, maglev trains float on a cushion of magnetic repulsion and attraction, enabling them to travel at high speeds with minimal friction and noise. This system entails that containers can travel autonomously, individually, adapting flexibly to the demand, with an efficient energy consumption and very low CO2 emissions.

The system's attributes are strategically aligned for addressing the intricate connectivity requirements between dry ports and primary seaports, inter-terminal links, and intra-container yard transportation. The maglev system's flexibility and speed makes it optimal for bridging the gap between dry ports and seaports, enabling just-in-time container deliveries at the berth for loading onto vessels. For inter-terminal transport, the system eliminates additional handling steps by providing seamless direct transshipment from berths to the corresponding terminal storage. This minimizes operational complexities, costs, time and uncertainties of using other transport systems as barges or trucks. Furthermore, by using this system for intra-terminal transportation, taking the function of automated systems as AGVs, the handling moves are minimized, as this one is connected efficiently to the storage, and the whole transportation network is integrated in one. However, the system also has to ability to work together simultaneously with AGVs if required, as its dedicated flexible and elevated infrastructure wouldn't interpose into the AGVs operations.

Nonetheless, as this is a new technology and there is no quantitative research on the topic, the system's integration into port logistics is unknown yet. The system's complexities and technical characteristics would require a completely redesigned port system, leading to many uncertainties regarding how would the system be implemented and what its performance would be. The main worry is generally regarding the capacity a system like this could handle, and if it could cope with a big port's volumes. This is the reason why this research is performed, in order to provide an understanding on the maglev technology integration.
However, given that this is a novel technology and lacks quantitative research, although there are some proof of concept performed by the company, the detailed design, integration of the system into port logistics and its performance remains unknown. The intricate complexities and technical features

of the system would require a substantially redesigned port system, depending on the current organization of each port, leading to uncertainties about its implementation and its subsequent performance. The primary concern revolves around the system's capacity and its ability to manage the substantial volumes typically associated with large ports. This research is undertaken precisely to address these uncertainties and contribute insights into the integration of maglev technology in port operations.

Figure 1.2: TSB Cargo, the maglev transport system from Max Bögl at the 860-meter test track in Sengenthal (Germany) . Source:Bögl, 2021.

In the literature, several papers on ports logistics, with a focus on the container movement, are available. See for example, Liu et al., 2002 who studied the usage of different means for intra-terminal transportation as AGVs, linear motor conveyance system (LMCS) or an overhead grid rail system (GR), testing their different terminal designs with a simulation. Or Truong et al., 2020, who proposed an innovative system revolving around individual automated electric rail for inter terminal transportation. Leriche et al., 2015 also devises a rail shuttle system, facilitating the connection between the hinterland multimodal terminal and seaport terminals. However, no paper proposes a system that is capable of performing the three types of transportation – intra-terminal, inter-terminal, and seaport-hinterland connections, while offering a direct connection to the berth, studying its performance and feasibility. Hence, in this paper, we aim to fill this knowledge gap by assessing and designing a new transportation system using maglev shuttles that can work well in this particular logistics setting, and for which no research for technology's integration and practical considerations into ports has been done neither. One of the primary challenges of this design is testing the feasibility and performance of a direct connection to the berth from the dry port, an aspect that has not been thoroughly explored.

To materialize the potential of this innovative solution, a systematic evaluation through design, simulation, and analysis becomes imperative. This research endeavors to construct a robust network and terminal layout, assess integration complexities, and address practical considerations like equipment requirement, transit times, congestion, and capacity, while analyzing the implications on efficiency, automation, and congestion mitigation. Initially, the plan entails employing the Weighted Sum Method to compare various network designs and identify the best performing options. Subsequently, these selected designs will be subjected to further refinement, taking into account operational implications and ensuring scalability to accommodate diverse volumes and port layouts. This structured approach aims to lay the foundation for the development of robust and adaptable solutions tailored to address the complexities inherent in port operations. The proposed simulation will provide insights into system dynamics, informing decision-making for real-world implementation by identifying bottlenecks, modeling operational complexity, and optimizing design alternatives.

In summary, this research aims to address the pressing need for efficient and sustainable container transportation within port ecosystems. The exploration of the freight maglev system's integration and performance within these contexts is positioned to provide transformative insights for optimizing trade logistics and reducing the ecological footprint of port activities.

1.2. Research objective

The primary goals of this study encompass the following key objectives:

1. Network and Terminal Design: Design a comprehensive network layout and terminal arrangement that accommodates the operational requirements of the maglev system. This involves integrating intra-terminal operations within the seaport, inter-terminal transportation, and establishing a seamless connection to the dry port. Hence, the system must effectively manage all container movements while ensuring they are completed on time. The complexity of the problem necessitates a comprehensive optimization with the goal of determining the most efficient design. However, due to the constraints of the research timeline and considering that this marks the initial exploration into the topic, the design of system and operational scheduling rules will be approached intuitively. The finer optimization of the system will be deferred to future research endeavors.
2. Simulation and Analysis: Develop a robust simulation model that faithfully replicates the operational dynamics within the proposed layout for this innovative technology. Through this model, analyze the interactions between the maglev system and handling equipment, assess performance metrics, and identify potential bottlenecks and operational implications under diverse scenarios.

By striving for these goals, the research contributes to provide and understanding on this technology, offering decision-informing insights to guide stakeholders in the effective implementation of the maglev system. Simultaneously, the designed system aims to bridge the gap between the seaport and the dry port, making this one a feasible solution. This research strives to revolutionize container transportation paradigms within ports, ultimately culminating in improved trade logistics, minimized environmental impact, and promoting sustainable progress within the maritime sector.

1.3. Research scope

As discussed in the literature review (Section 2.2), the research accommodates functions of many different papers, as the system combines many different transportation functions. Therefore, the research has to be scoped down to the main focus.

The primary emphasis of this study centers on the design and modeling of a terminal network, specifically targeting one seaport terminal and its interaction with the adjacent dry port terminal, depicted in Figure 1.3. The scope also includes external terminals, consisting of two container and a barge terminal, integrated into the simulation as black boxes, with inflow and outflow of containers. It is assumed that flows passing through non-modeled terminals remain smooth and free from congestion. However, a buffer time will be added to vehicles when passing through them to simulate their stance in these external terminals. While the rest of flows at the main terminal and dry port will be modelled, rail operations, truck operations at the dry port and storage will just be qualitatively considered for design purposes without explicit inclusion in the simulation. The central focal point is the efficient loading and unloading of vessels, as their berth times stand as a main key performance indicators for major port stakeholders. Cost analysis falls beyond the scope of this research, which primarily seeks operational feasibility and will only touch upon cost considerations briefly in the discussion. Even tho, costs will be taken into account in order to generate a reasonable design.

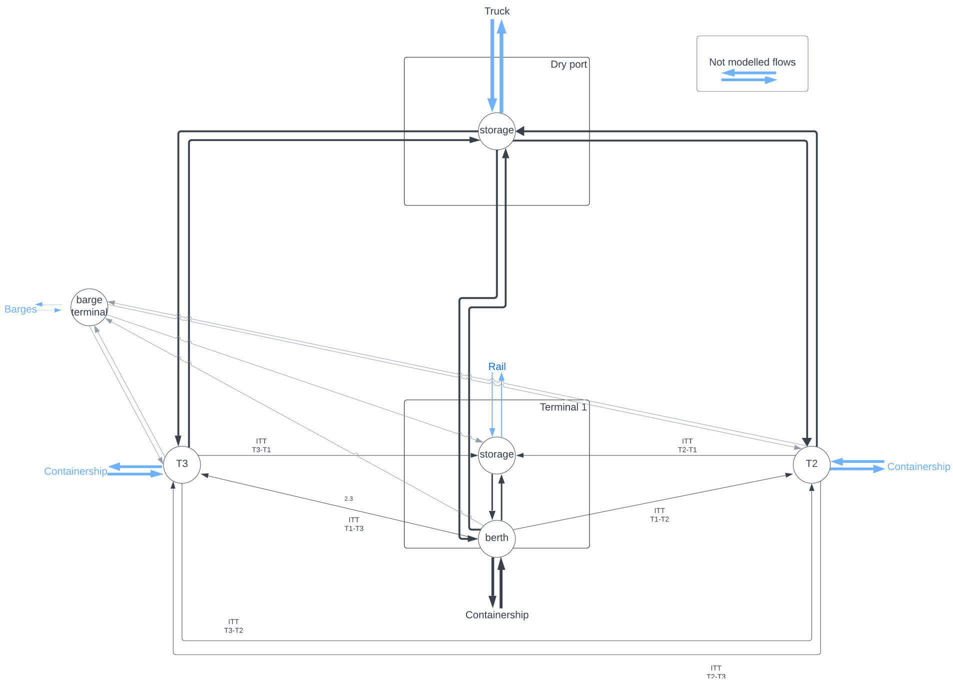

Figure 1.3: Network flows sketch. Blue arrows indicate the inflow and outflow out containers in the system that are not being modelled in the simulation study.

This research operates in collaboration with Max Bögl, the proprietor of the ’TSB Cargo’ maglev transport system innovation. Hence, this thesis project combines the academic and business approaches. TU Delft’s focus lies in addressing the knowledge gap by developing an integrated system encompassing inter-terminal, intra-terminal, and dry port transportation, with a direct berth connection, while adding to research practical insights into the operational applications of maglev technology. On the other side, the company’s interest lies in the integration of their maglev system into port logistics, leveraging the findings to shape future projects and attain insights into the system’s design and operational implications. These two approaches converge harmoniously within this research.

1.4. Main research question & sub-questions

Based on the goals described in section 1.2 the main research question is constructed. Answering the following question will lead to achieve those objectives:

How can a maglev transport system be integrated into seaport logistics,

connecting it to a dry port,

and how would the integration impact port operations?

This main research question can be answered treating the following sub-research questions:

1. Which are the possible system designs & layouts for integrating a maglev transport system into seaport logistics, connecting this one to the dry port ? (Chapter 3)
2. What is the performance of the system designs? (Chapter 5)
3. What would be the impact of integrating a maglev transport system in port logistics? (Chapters 5 and 6)

2 Background

To gain a deeper understanding of port processes, the various transportation methods employed, and the existing research in this domain, this background chapter is structured as follows: it begins with an analysis of port processes in Section 2.1, delves into a comprehensive literature review in Section 2.2, and finalizes with a conclusion.

2.1. Current terminal operations & processes analysis

In the world of container terminal operations, significant changes have occurred, largely driven by global trade and new technologies. Containerization, a system of transporting goods in large, standardized containers, has made a huge impact on how things move around the world. While the early strides in this field centered on optimizing equipment, such as cranes and trucks, the pivotal role of skilled human operators remained needed. However, starting in the 1990s, this began to change rapidly as automation started to play a big role in container terminals. As we explore how container terminals work in this chapter, it's important to understand this shift towards automation (Chuanyu et al., 2003).

The move towards semi-automated and fully automated systems happened because of several important reasons. These include need for operations standardization, reduction of manning, increased handling capacity, and productivity improvements (Knatz et al., 2022). Automated container terminals (ACTs) offer many advantages in efficient, accuracy, safety, 24hrs and any weather operation, operational costs savings, and carbon footprint (Chuanyu et al., 2003). It's worth noting that not all terminals have gone fully automated. In fact, only a very small number, about 3% (63) of all container terminals worldwide, have made this change. And of these, only around 29% (18) are fully automated. However, these are the more advanced ports where innovations are more likely to be applied, and therefore in this analysis, we will be mostly focusing on automated and semi-automated ports. These terminals often serve as industry pioneers, pushing the boundaries of technology and efficiency in container handling. Therefore, by concentrating on these we can gain valuable insights into the cutting-edge practices that are shaping the future of terminal operations.

In a semi-automated terminal, the automation is primarily focused on the vertical movement of containers within the yard. In contrast, a fully automated terminal extends automation to both the vertical and horizontal movement of containers. This includes handling containers from the berth, also known as the quayside, to the yard, where containers are stacked. In respect of the terminal sizes, the average size of automated ones, 98.6ha, is 17.2% larger than semi-automated ones . Additionally, automation can also be implemented in the fourth critical area of a container terminal, known as the in-out gate function. This aspect of automation primarily deals with automating the entry and exit of trucks into the terminal. However, it's important to note that when distinguishing between fully and semi-automated terminals, this specific type of automation at the in-out gate is typically not considered (Chuanyu et al., 2003).
However there are also small levels of automation in its simpler form, as using information technologies to manage terminal assets, supplementing human activity. At the center of this transformation stands

Figure 2.1: The new Victorian International Container Terminal (VICT) at Webb Dock East in Melbourne (Muldowney, 2019).

the Terminal Operating System (TOS), a software controlling and optimizing the movement fand storage of containers in and around the terminal. Taking the function of the terminal's brain, with also the use of other technologies, allows the terminal to optimize its assets, labor and equipment, with real time information for cost-effective decision making (RBS Terminal Operating System, 2023).

As we dig deeper into how terminal operations work in this chapter, we'll break it down into three parts: (1) seaside, (2) yard-side, and (3) landside. This will be followed by a fourth section analyzing the (4) port main stakeholders. It is also worth mentioning that as import (sea to land) and export (land to sea) terminal operations are symmetric, operations are just described in one direction in order to avoid redundancy.

2.1.1. Seaside operations

In the domain of container terminal operations, the primary objective for port operators is efficiency. This multifaceted goal encompasses the minimization of vessel turnaround time, the maximization of quay crane productivity, and the enhancement of container terminal throughput. A crucial aspect of this optimization journey is the orchestration of a vessel's arrival at the port, often referred to as a "port call" or "vessel call." This process encompasses the vessel's approach to the harbor, its mooring at the berth, cargo handling operations, and all associated activities during the vessel's stay at the port. These activities are meticulously planned to ensure seamless execution. The challenge lies in efficiently assigning berthing positions and service times to optimize berth allocation while accommodating the requirements of shipowners.

Container terminals, each unique in terms of quay sizes and shapes, may have varying layouts. Beyond the standard single long quay, terminals with multiple discontinuous quays may adopt different configurations. These layouts include pier-type, basin-type, or natural-type layouts, dictated by the shape of the shoreline (Figure 2.2). The average quay length of semi-automated and automated terminals is 1480m (Chuanyu et al., 2003). Furthermore, berth space can be categorized as discrete, continuous, or hybrid. Discrete berth space entails predefined berthing positions, allowing one vessel to occupy each berth. In contrast, continuous berth space permits vessels to moor anywhere within the quay space. Hybrid berth space combines predefined berths with the possibility of vessels occupying more than one berth or sharing a berth (Carlo et al., 2015).

Figure 2.3: Cargo containers are transfered from QCs to AGVs at a fully automated container terminal of the Port of Qingdao in east China's Shandong Province. (Xinhua, 2018).

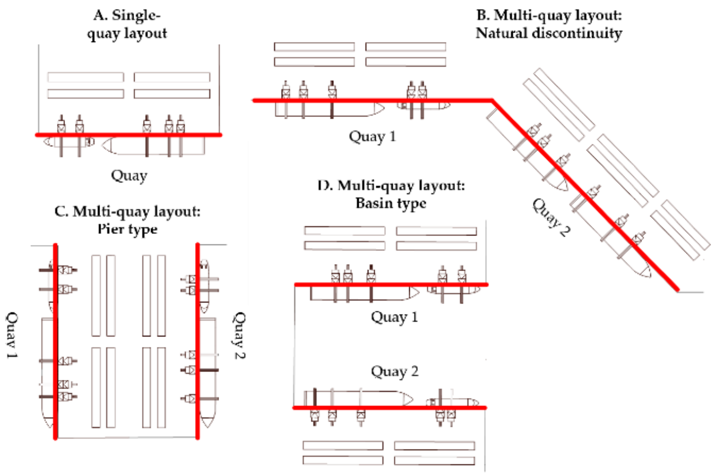

Figure 2.2: Different quay types (Grubisic et al., 2020).

At the heart of seaside operations, quay cranes (QCs) play a pivotal role in loading and unloading vessels. These sizable machines are positioned alongside the quay and move in parallel to the berth on rails. However, they cannot pass each other. The challenge here is the allocation of cranes to vessels to ensure the efficient transshipment of containers. QCs often represent the bottleneck in port operations, making their allocation and utilization a critical aspect of optimization.

Once containers are lifted from containerships by quay cranes, the unloading process depends on the type of transfer vehicle used to move containers between the seaside and the yard storage. These vehicles fall into two categories based on their ability to independently lift or drop containers from the ground or their reliance on handling equipment. The primary categories for automated vehicles are Automated Guided Vehicles (AGVs), and secondly lift-AGVs and Automated Lifting Vehicles (ALVs), with AGVs requiring quay crane assistance to lift containers. This reliance on QCs necessitates synchronization and a higher number of AGVs to prevent QCs from waiting—an issue as QCs are often the bottleneck and a costly resource (see Figure 2.3). In contrast, lift-AGVs, are similar to regular AGVs, however they have a horizontal lifting mechanism that allows to place (or pick) containers from racks. Similarly, ALVs can independently lift (and drop) containers from the ground. Consequently, QCs do not need to wait for available lift-AGVs or ALVs and can stack (or lift) containers in a rack for the former, or buffer area for the second one, at the quay crane's apron and transfer point (TP). ALVs or lift-AGVs subsequently retrieve the containers and transport them to the storage yard. Other non-automated horizontal transport equipment can also be used, as are the yard truck (YT), straddle carrier (SC), reach stacker (RS) or prime movers.
Typically, unloading is conducted first, followed by loading, with only a brief overlap where both opera-

tions occur simultaneously. This results in about half of the transporting trips having an empty vehicle. However, recent studies and implementations in some ports have explored a method known as ”double cycling” or ”dual-cycle.” This approach combines unloading and loading operations simultaneously (see Figure 2.4). Models developed for this process optimization, as in Goodchild and Daganzo, 2006 or Ku and Arthanari, 2014, aim to enhance the efficiency of quay cranes and horizontal transport vehicles. Given that QCs are often the bottleneck in terminal throughput, adopting double cycling strategies for quayside operations at seaports represents a valuable option to boost terminal productivity. Additionally, it can lead to energy savings by reducing empty horizontal transport trips (Ku and Arthanari, 2014).

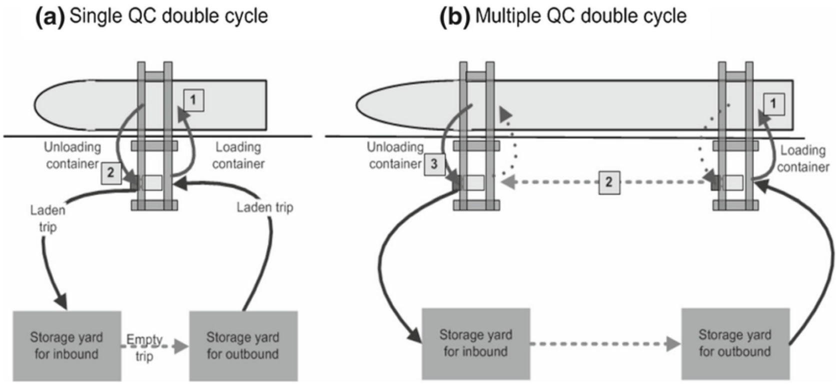

Figure 2.4: Single cycling vs double cycling processes at berth (Ku and Arthanari, 2014).

2.1.2. Yardside operations

Continuing from the seaside operations, the journey of a container proceeds to the yard side once it’s loaded onto the transfer equipment. Here, a yard crane takes over, responsible for safely storing the container in the stack. Container terminals employ various types of yard cranes for these storage and retrieval tasks, with rubber-tired gantry cranes (RTGs) and rail-mounted gantry cranes (RMGs) being the most prevalent choices. RTGs, equipped with rubber tires, traverse over containers and can move freely among blocks, while RMGs operate on rails, typically serving a single storage block. Both RTGs and RMGs offer advantages such as high-density storage and short cycle times.

At the tactical level of planning, a crucial decision revolves around determining the number of yard cranes required to ensure an efficient storage and retrieval process. For a given space, deploying more yard cranes reduces response times for retrieval requests but increases facility investment. In essence, a trade-off exists between storage density, accessibility, investment costs, and service levels. Additionally, the efficiency of the transport system, governed by rules for dispatching, scheduling, and routing vehicles, plays a vital role in mitigating congestion and enhancing overall port performance.

The operational dynamics of container terminals often encounter uncertainties in vessel arrival, resulting in containers being picked up in an order inconsistent with their initial stacking positions, leading to the need of re-marshalling. Traditional container terminals typically store import and export containers in separate blocks, enabling a focus on coordinating space management with yard crane scheduling to minimize re-marshalling costs. However, automated container terminals (ACTs) typically integrate import and export containers within the same block. Yard cranes are then tasked with transferring these containers from the block’s end to a handshake area for subsequent loading or retrieval, making re-marshalling an unavoidable aspect of ACT yard management (Yu et al., 2022).

Container yards are typically divided into large zones, further subdivided into rectangular-shaped blocks. Two primary storage layouts are prevalent in ACTs: the parallel and perpendicular layouts, which can be seen in Figure 2.5. In the parallel layout, blocks encompass multiple lanes for container stacking and one lane for trucks to pick up and deliver containers. These blocks are organized into modules, which consist of two blocks with transfer lanes between them. The perpendicular layout, more commonly employed, involves longer container stacks with two transfer points—one at the berth side for loading and unloading containers to and from internal transport equipment, and another at the land-side for external truck pickup or transshipment to other transport modes. Some terminals also allocate separate stacks for empty containers or reefers.

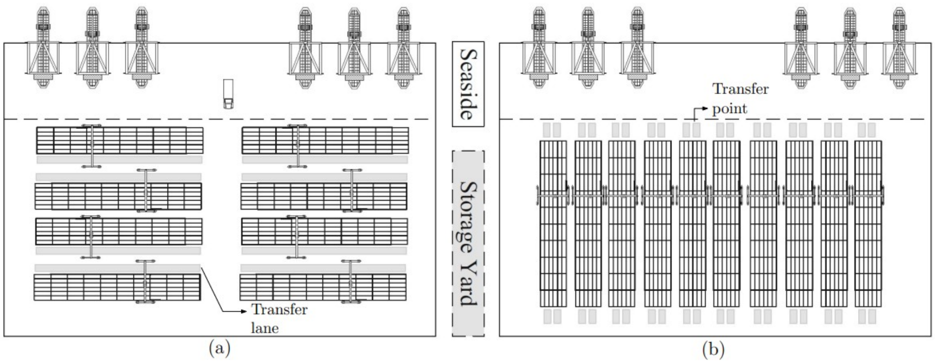

Figure 2.5: Parallel stack layout with transfer lanes and Perpendicular stack layout with transfer points (Akash Gupta and Parhi, 2017).

Container yard management has embraced automation for years, relying on information systems to oversee the stacking of inbound and outbound containers. Automated yard management mandates container position determination systems equipped with sensors, ensuring that the location of all containers within the terminal is continually monitored. This real-time information enables efficient container management, facilitating rapid retrieval for ship loading or pickup for inland distribution (Notteboom et al., 2022).

2.1.3. Landside and transshipment operations

Following the container's placement in the designated yard area, this one becomes ready for various downstream operations, each subject on its ultimate destination. These operations comprise customer pickup, either by truck or through intermodal modes like rail or barge, typically associated with local import scenarios. Alternatively, containers may undergo second-carrier loading at the same or different terminal, a practice commonly referred to as transshipment.

Nowadays, road-based haulage remains the dominant mode for hinterland transportation to and from ports, across most regions globally. However, Port governance systems, particularly in Northern Europe, have influenced implementing initiatives aimed at promoting modal shifts in freight transportation. These ports have emerged as leaders in executing strategies geared toward transitioning freight from road transport to more sustainable alternatives, such as rail and waterborne modes (Gonzalez-Aregall et al., 2021).

The implemented maglev system will take the function of current ITT operations and its connection to the inland waterways mode will just be treated as an additional terminal, as with this implementation barges will not need to call at each terminal. Moreover, the system will interact and impact rail operations at the seaport terminal, and road access will be moved to the dry port, also taking part of the system's design. Therefore, this subsection enquires into an analysis of the ITT, road and rail current processes at the port, seeking to provide insights into these, in order to be able to adapt the current port logistics into the newly designed system. An example of the container flows distribution at a port currently is shown in Figure 2.6.

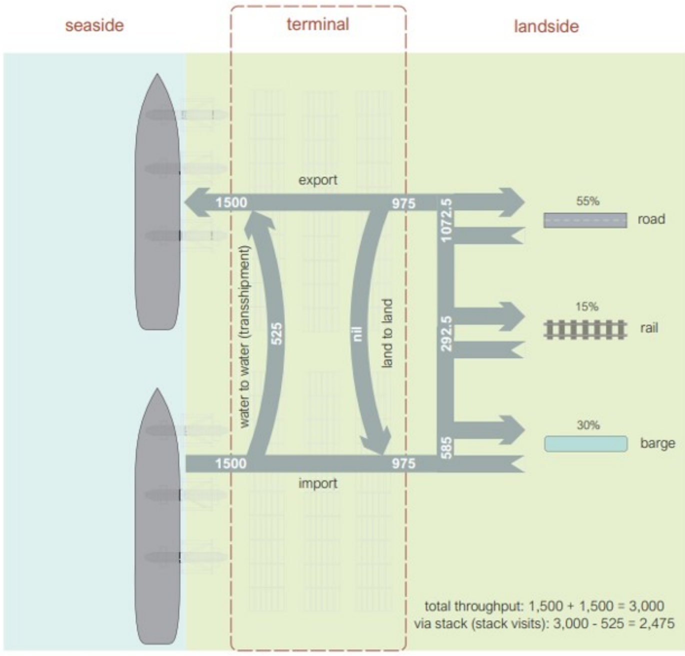

Figure 2.6: Container flows and modal split example (numbers × 1,000 TEU/year) (Quist et al., 2021).

Interterminal transportation (ITT)

Interterminal transport (ITT) denotes the movement of containers between various terminals. This encompasses container terminals, empty container depots, logistics facilities, dedicated transport terminals (barge, rail terminals and dry ports), and administrative facilities (e.g., container screening and customs clearance) (Adi et al., 2020). The ITT process utilizes mainly road, rail, or barge transportation modes, and even terminal equipment when terminals are located close to each other. Despite the availability of these options, trucks continue to dominate cargo transportation in many ports and are projected to maintain their prominence in the future (Adi et al., 2020). There are critical parameters and decisions that impact port planning and operations, including terminal layout, interterminal connectivity, the type and number of vehicles employed for ITT, and the scheduling of these vehicles (Bandara, 2017).

The overarching goal of an efficient ITT system is to facilitate the timely transfer of containers between terminals while minimizing delays, transport time, and costs. Key objectives encompass the reduction of handling times, achievement of high occupancy rates for vehicles, minimization of empty trips, and the mitigation or avoidance of disruptive traffic congestion that can adversely affect the productivity and efficiency of ITT operations (Heilig and Voss, 2017).

Interterminal transfers can be abundant, especially in pure transshipment ports. These ports serve as nodes where container ships of varying sizes, operated by different carriers on diverse routes, converge. In contrast, gateway ports, where containers are directly transported to their hinterlands without an additional sea leg, generally involve fewer interterminal moves. However, not all terminals in gateway ports have direct access to trains or barges, necessitating interterminal transfers, particularly for transport to multimodal terminals (Forum, 2021).

Concerning transport infrastructure, some ports opt for dedicated facilities to facilitate ITT, such as non-public roads that enable the use of more efficient and/or autonomous terminal equipment, including multi-trailer systems (MTS) and automated guided vehicles (AGVs).

Efficient coordination of inter- and intra-terminal operations presents a substantial challenge, necessitating the use of collaborative planning techniques and real-time communication channels to streamline processes and optimize ITT operations within the complex port ecosystem.

Inland waterway transportation, particularly via barges, presents a persuasive mode of cargo transit, offering a clean and cost-effective means of reaching inland areas, along with the advantages of economies of scale and density, making it a competitive choice compared to truck-based transportation. As discussed, in certain ports, barges integrated inland waterway transport and Inter-Terminal Transportation (ITT) by making calls at each terminal to collect containers for inland waterway transit, thus also loading and unloading performing the ITT service. However, with the introduction of the maglev system, the necessity for ITT services by barges becomes obsolete, consolidating all operations within a designated barge terminal. Consequently, the maglev system views the barge terminal as a supplementary container terminal.

Road

Truck operations within the hinterland of container terminals involve a well-structured process that begins at the terminal's entry and exit gate. Trucks enter the terminal at this point, and their journey is initiated with a complete inspection. The primary objectives of this inspection are to verify the readiness of all required documents for pickup or delivery and to assess the condition of containers. Modern management systems have transitioned away from traditional paperwork, as all documentation is now stored electronically and securely transmitted through digital connections, as well most of this inspection is conducted remotely using advanced technologies such as cameras and intercom systems. Through these means, an operator can remotely access crucial information, including the container identification number, and cross-verify it with the bill of lading (Rodrigue, 2020). To optimize service efficiency and mitigate extended waiting times at the gate, appointment systems have been implemented.

Following the gate inspection, the terminal provides the specific storage location within the yard for each outbound and inbound container. The truck proceeds to this designated location, known as the "transfer point," situated within a block of container stacks. At this location, a Yard Crane (YC) comes into play, engaging in either a "receiving operation" by accepting a container from the truck or a "delivery operation" by providing a container to the truck (Kim et al., 2012). Following this, the truck proceeds to exit the terminal, undergoes an inspection to verify the correct container has been loaded, and proceeds with its journey inland.

Efficient management of this process, often facilitated by appointment systems, ensures that containers are readily available for pickup. However, it's important to note that pickup delays can occasionally become significant, particularly when a large containership has just unloaded a substantial batch of containers. During such peak periods, there's often a rush to be among the first to claim these containers, potentially leading to delays lasting several hours. Recognizing the importance of optimizing gate throughput, terminal operators have invested substantial efforts in recent years, focusing on gate design enhancements and the integration of information technologies, including the aforementioned appointment systems, to streamline operations and enhance overall efficiency (Notteboom et al., 2022).

Even with an efficiently managed gate service and a well-functioning appointment system in place, the substantial and ever-increasing volume of containers poses a persistent challenge to the infrastructure in the vicinity of the port (Lange et al., 2017). This congestion gives rise to issues of unreliability, extended waiting times, and an elevated carbon footprint. Consequently, there exists a high need of reducing the influx of trucks at the port and explore alternative transport modes. Many ports find themselves nestled within urban environments, where the existing infrastructure is not able to accommodate the high volume of transportation activity. This high volume of truck traffic not only affects the port's operations but also has significant repercussions for the quality of life and safety of the city's residents.

Rail

A significant number of terminals are equipped with their own rail transshipment facilities, solidifying their role as multimodal hubs where the railway sector can significantly expand its market share (Pagand et al., 2020). From an environmental perspective, rail freight traffic holds considerable appeal. When measured in tonne-kilometres trucks emit a staggering 110 times more CO_2 than trains (HHLA,

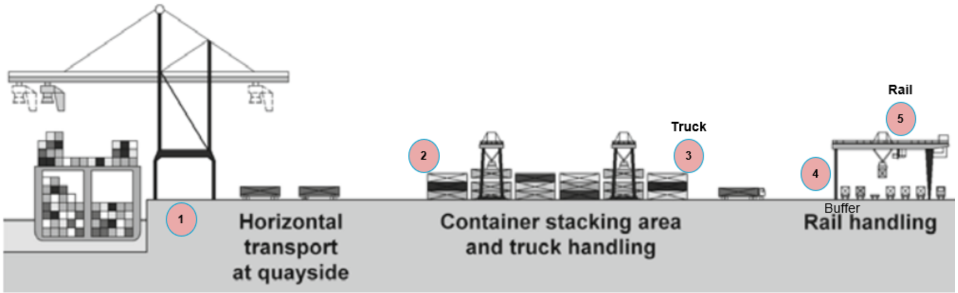

Figure 2.7: Terminal operations handling moves. As can be seen, road transport needs 3 moves while rail transport needs 5. (Adapted from Brinkmann, 2011).

2021).

Upon arrival to the port, the freight train is divided based on the destination terminal for each container. Once settled at the terminal unloading process starts. This operation is typically performed using rail-mounted gantries, rubber-tyred gantries, or other specialized equipment.

Unloading and loading operations involving trains within the maritime terminal must adhere to specific time windows. Export containers are unloaded and prepared for loading onto ships. However, greater attention is required for managing import containers to ensure efficient loading onto trains. Import containers are stored first at the general terminal yard and then, before the expected railcar arrival, are transported to a dedicated area closer to the tracks, functioning as a buffer. For the storage at the buffer area, the terminal adopts a pre-marshalling strategy to have containers ready near the tracks, eliminating the need for reshuffling and other movements within the storage area. This strategy aims to reduce the cycle time of Yard Crane (YC) operations. Prior to this, there is the train load planning problem, which involves determining the appropriate wagon for each container based on factors such as its destination, type, weight, wagon capacity, and the container's location in the storage area. The effectiveness of space allocation depends on the availability and accuracy of arrival and departure time information.

Presently, the rail cargo sector, especially in Europe, faces complexities that make it less competitive compared to truck and barge transport modes. While innovative ideas exist, true innovations within the rail cargo sector are relatively rare. Consequently, rail transport remains traditional and somewhat outdated in many cases (Ambrosino et al., 2021). Rail transportation are further disadvantaged and undesired by terminal operators, as these ones require two additional handling moves compared to truck transport (as illustrated in Figure 2.7), while generally the same handling fee is charged.

Traditionally, the transport of containers to the rail area is done using non-automated equipment such as reach stackers, straddle carriers, or yard trucks. However, some terminals have embraced automation in recent times, exemplified by APM Terminal in Maasvlakte, Rotterdam. This terminal employs a highly automated system featuring lift-AGVs, which place containers on racks adjacent to the rail tracks, from where they are subsequently retrieved by automated ARMGs and loaded onto the railcars (APM, 2023).

2.1.4. Main stakeholders

Stakeholder analysis is an essential process for any logistics project, especially when designing and integrating an innovative transport system. Logistics is a complex and interconnected industry, with many different parties involved in the movement of goods. Automated transport systems can have a significant impact on the operations of existing stakeholders and create new opportunities. Stakeholder analysis can help to identify and address current issues and maximize opportunities, ensuring that the system is designed and implemented in a way that benefits all stakeholders involved. In a market like this one, in case of designing a system without the approval of all of the main parties the implementation of it would be practically impossible, and therefore the importance of analyzing this prior to designing. The analysis allows to set objectives and boundaries for the later design.

In the realm of port projects, two primary stakeholders typically emerge as the key project owners: the port authority and the various terminal operators. Ports and terminals cater to a diverse array of customers, with shipping lines or carriers occupying a paramount position due to their market influence. The consolidation of the liner shipping industry, driven by mergers, acquisitions, and alliance agreements, has strengthened carriers' market power, particularly evident on the quayside of terminals (Castelein et al., 2019). Beyond shipping lines, other significant stakeholders include cargo owners, freight forwarders, trucking companies, barge operators, railway companies, customs authorities, and various logistics service providers, as well as government agencies. Each of these parties possesses unique interests and requirements, particularly concerning projects such as the integration of a maglev system connecting the seaside with storage yards, other terminals for inter-terminal transportation, and dry ports.

The port authority, whether public or private, holds the responsibility, under national law or regulation, for administering, developing, managing, and occasionally operating port land and infrastructure. Their primary objective is to ensure safe, sustainable, and competitive port development (Larissa et al., 2023. In the context of the maglev project, the port authority is interested in eliminating pollution, improving port access, enhancing connections to the hinterland, optimizing inter-terminal transportation, facilitating links with other transportation modes like rail, and improving terminal efficiency to boost overall port competitiveness.

Terminal operators lease port terminals through concessions, a model that evolved as a response to the increasing demands for private investment in ports, and as an intermediate form of privatization, leading to various forms of public-private partnerships (Notteboom et al., 2022). Terminal operators, as private entities, aim to maximize profits while adhering to the port authority's guidelines. Efficiency in terminal operations is key to achieve this profit maximization. For projects like the maglev system integration, terminal operators seek to improve operational efficiency while coping with the existing infrastructure, customer demands, and equipment capabilities. Efficiency gains are critical, as innovation should not introduce additional handling steps into processes. Furthermore, enhancing the connection with rail transportation, addressing a common terminal operations weakness, is a key consideration. Customer interests and requirements play a pivotal role in the innovation implementation, which are discussed below.

Carriers is a key stakeholder group do to the high power they have on the market. When selecting a port, carriers consider vessel turnaround time as a critical factor alongside pricing. A shorter turnaround time allows carriers to execute more sailings, increasing revenue (MarineTraffic, 2023). Additional factors include shipping volumes to and from the port, reliable terminal equipment, and efficient connections to hinterland transportation modes, such as rail and road. Therefore, the maglev project must not increase vessel turnaround times and must maintain system reliability and connections to other modes.

Truckers' interests revolve around the access to terminals, mitigating the congestion issues that affect many ports, leading to high waiting times and therefore losses for trucking companies. They seek an efficient gate-in process and smooth interactions with terminal handling equipment. The implementation of container drop-off and pick-up at a dry port may benefit truckers, offering improved accessibility closer to the hinterland. However, it may reduce the demand for trucking services in the port surroundings, particularly for inter-terminal transportation.

Rail and barge operators prioritize the reliability of container loading and unloading operations to maintain predictable cargo handling schedules. Improved efficiency in these operations can expand network capacity, as well potentially leading to volume increases. Similar than for trucking, if the maglev system is employed for inter-terminal transportation, it may reduce the reliance on rail and barge modes.

Shippers and freight forwarders, as main actors on the transport demand side, play a pivotal role in influencing port volumes. When choosing ports, their criteria include location, multimodal connectivity, pricing, and reliability.

For local communities, port terminal innovations can impact their life quality. Innovations are of particular interest in terms of pollution reduction, safety improvements, reduced strain on public infrastructure, and potential job creation. High truck volumes passing through cities to reach ports can lead to congestion, safety concerns, and pollution. Implementing a dry port solution for handling truck containers can alleviate these issues by reducing truck arrivals at the port and consequently enhancing the quality of life. The maglev system, being silent and non-polluting with dedicated infrastructure, poses no adverse effects on the community (Notteboom et al., 2022).

2.2. Literature review: Port transportation methods

In this literature review, we will explore different ways that containers are transported (1) within ports, (2) between terminals, and (3) from ports to inland terminals. Various methods and research related to them will be reviewed, as well the methods used. This review will help us better understand the options available for improving transportation systems between different parts of the port and finding ways to integrate them effectively. Therefore, the research question for this literature review is the following:

"What are the various container port transportation methods, and what methodologies are employed to study their integration and effectiveness within different parts of the port logistics?"

Intra-terminal transport

Within the area of container yard operations, a research focus of great importance revolves around the equipment or machinery employed to facilitate the movement of containers, encompassing the transition from the ship's berth to the storage yard or onto trains and trucks for outbound transport for import, or the other way around for export operations. Another crucial point of focus is terminal's layout, as this significantly impacts their efficiency. The primary objective is to make these processes faster and more cost-effective by minimizing the number of handling movements or increasing their efficiency.

Kap et al., 2012 conducted a study that evaluated qualitatively various methods of container movement as quay cranes, AGVs, etc., and other newer concepts as AR/RS (automated storage and retrieval system), linear motor conveyance system (LMCS) and overhead grid rail (GRAIL). The paper assessed these methods based on criteria such as flexibility, cost implications (both construction and operation), environmental impact, resilience in case of malfunctions, and the ease of maintenance. The study's findings suggested that integrating tasks like moving, stacking, loading, and unloading containers into the same equipment piece could lead to quicker and more efficient processes, ultimately improving overall operational performance. Liu et al., 2002 also tackled the usage of these technologies, however from a quantitative perspective, by developing four distinct terminal designs and testing them with a simulation, showing the potential of automation to significantly enhance terminal performance without incurring high costs. The LMCS and GRAIL systems discussed in these papers can be compared to the maglev application for intra-terminal transportation, as containers are transported on a fix path guide network, however, do to some different characteristics as the guideway itself or higher speeds, the intra-terminal routing would have to be designed differently. The benefit of using the maglev system instead of these ones is its ability to be able to transport the containers to the inland ports as well, as there is a big difference in the peak speed reached by these systems (below 10km/h) to the maglev one (150km/h (Bögl, 2021)), being therefore able to integrate the intra-terminal transportation and the transportation outside of this one, and therefore decreasing the number of handling movements.

Building on this work, *Liu2004* extended the research to investigate how different terminal layouts impact the performance of AGVs. They employed computer simulations to compare two common terminal layouts, one with the container stacks parallel to the berth and another one perpendicular. The research concluded that the AGVs increase substantially the terminal's throughput, however the yard layout has a critical effect on the performance of this one, as well as on the number of AGVs required. Similar to this one, *Xiangda2021* follows the previous papers on terminal layouts, evaluating via a novel agent-based simulation model the following four different designs: a parallel and a perpendicular layout design for non-cantilever ARMG systems, and a U-type and a parallel layout design for bilateral-cantilever ARMG systems. Results show that U-type automated terminals gain the lowest energy consumption and operational cost, in most of cases outperforming perpendicular layout in terms of operations efficiency and waiting times. In this research we will also test different layouts for the terminal, having also parallel and perpendicular setups; modeling the QCs and RMGs as well. Nonetheless, the layouts and equipment interaction will differ due to the utilization of the maglev system instead of AGVs for yard transportation, which navigates through a fixed infrastructure. Additionally, there will be a distinction in the seaport terminal storage, encompassing transshipment and rail storage while road operations will be conducted at the dry port. Similarities arise in the simulation's KPIs, specially such as ship waiting time

Moreover, D'Ariano et al., 2018 studies multiyards railway intermodal terminal (MYRIT) layouts, with a detail simulation of train moving processes to evaluate various design options. In my study, for the terminal design side there will be a focus on optimizing train terminal operations, however rail loading interactions will not be modeled in the simulation. Furthermore, D'Ariano et al., 2018 's terminal design is based on truck-rail and rail-rail transshipments, while my research's terminals will have on the port-side sea-rail transshipments and at the dry port storage-road, with the connection between sea and dry port storage done with the maglev system.

Inter-terminal transport

Inter-terminal transportation (ITT) research centers on the exploration of diverse transport means and models aimed at optimizing the movement of goods between terminals. Duinkerken et al., 2006 conducted a study within the context of the Maasvlakte container terminals (Port of Rotterdam), undertaking a comparative simulation study evaluating different transportation systems for ITT, namely the multi-trailer system (MTS), automated guided vehicles (AGVs), and automated lift vehicles (ALVs). Evaluation criteria encompassed non-performance percentage per number of vehicles, late container delivery per hour, utilization, total moves, average number of vehicles at a service level of 99%, and the assessment of service rates vis-à-vis system costs. The experiments provided valuable insights into the intricate interplay between transport system characteristics and their interaction with handling equipment. In addition to these ITT systems, Truong et al., 2020 proposed an innovative system revolving around individual automated electric rail. The layout of this system was meticulously designed and subjected to thorough analysis, validating and testing its efficiency through simulation, focusing on a scenario grounded in projected ITT demand and available handling capacity at Busan Newport for the year 2030. The authors presented a mathematical model to determine essential parameters such as the number of shuttles and loaders based on the anticipated transport demand scenario, thus providing a robust framework for system optimization prior to simulation.

In comparison with these two papers, in my research, the transportation focus will only center on the connection between the dry port terminal and a selected seaport terminal, encompassing inter-terminal transportation with other seaport terminals as incoming and outgoing flows. The reason for this is that, differently than these two discussed papers, which just model every terminal as a singular node; in this study the whole intra-terminal transportation (in dry port and seaport) will be modeled accurately with all the terminal equipment interactions, as quay cranes and RMGs, at different yard locations. Nevertheless, commonalities exist with these studies, manifesting in aspects such as inter-terminals flow modeling and the application of shared KPIs. Furthermore, similar to the second paper, the transportation mechanism, automated electric shuttles, aligns conceptually, characterized by automation, operational autonomy, flexible demand response, and adherence to a fixed rail route.

Seaport terminals - inland terminals transport

The literature concerning transportation means linking seaport terminals and hinterland terminals focuses predominantly on innovative transport solutions, given the limited existing systems aside from conventional road and rail connections. Consequently, these papers take a broader perspective, emphasizing design aspects and the integration of new technologies into the port terminals' operations.

Hansen, 2004 highlights the pivotal role of enhancing rail competitiveness in intermodal-container transport through increased train frequency and efficient transshipment processes. Proposing an innovative solution developed by TU Delft, the study introduces linear motor driven wagons with center coupling. This innovation allows for highly flexible train formation at marshalling yards. Similarly, Gattuso and Cassone, 2018 proposed the use of an intelligent rail wagon called Automated Guided Wagon (AGW), also emphasizing on the handling movements and the minimization of handling costs. This system operates the container transportation from any suitably equipped area at the terminal to an adjacent station for the final composition of the convoy and for its placing on the line. The research created network models for the schematization and simulation of container handling in the yard, and cost models for evaluation of monetary impact, comparing the actual operating handling systems (RTFG, straddle carrier, AGVs, etc) to the AGW technology. It is therefore concluded that the use of these technologies allows to decrease the number of handling movements, bringing therefore high cost and time savings. These systems are similar to the maglev shuttles one, however these ones are just looking for train formation and not for a connection to a dry port and road transfers.

Rosa and Roscelli, 2009 introduces a transport system comprising automated electric rail shuttles designed to carry double-stack containers within the port of Genoa. Listing the same concerns highlighted in this literature review, the paper addresses issues such as urban encirclement of the port, accessibility challenges, road congestion, and capacity limitations for the port and city of Genoa. The proposal involves establishing a dry port connected to the seaport by this innovative transportation mode. This system and layout resemble the one proposed in my research, however this setup relocates all container storage, rail and truck loading/unloading to the hinterland, leaving the container yard totally empty, while mine only relocates road transfer storage. In addition, the proposed system doesn't seem to be scalable or to be able to handle large volume vessel in a timely manner. The paper only designs the system qualitatively without testing its performance, while in this research the performance will be tested through a simulation. Moreover, the study by Rosa and Roscelli, 2009 only presents the conceptual layout, without any quantitative research to test this one, unlike mine, which will make use of a simulation for it, in addition to considering also other port elements.

Similarly, Leriche et al., 2015 devises a rail shuttle system for le Havre port, facilitating connection between the hinterland multimodal terminal (acting as a hub) and seaport terminals. Differently than the previous paper, a multi-paradigm simulation tool is used, testing two allocation strategies for trains and shuttles to rail yard tracks: one based on priority coefficients and another on hybrid handling. This system follows a fixed schedule and performs train formations, whereas the maglev system adjusts to demand, enabling the individual transportation of containers and offering greater flexibility in delivering them to precise destinations, with the possibility of a just-in-time berth container delivery. Additionally, once containers arrive at the maritime terminal, they are typically placed in storage or buffer yards, which does not contribute to minimizing handling movements. An additional point of distinction from the referenced paper is that the rail shuttle handles transshipment for rail and river containers, whereas the maglev system we explore deals with incoming and outgoing road containers, connecting the seaport and the dry port.

Pourmohammad-Zia et al., 2020 and Wang et al., 2018 both explore the usage of AGVs for connecting the seaport to a hinterland terminal. The former investigates AGV platooning for hinterland connections, showcasing benefits in reducing costs, dwell times, and emissions. Similarly, the latter proposes AGV integration for an island port with limited space, demonstrating energy cost and CO2 emission reductions. These studies parallel my research in the quest for innovative transport means as solutions for connecting the mentioned terminals and therefore expanding the port capacity and its accessibility, however the port operations as loading, unloading and equipment interaction are simplified, due to the characteristics of the AGVs system. In this research, as we are treating a transport system in a guideway there might be congestion and queuing at the loading and unloading facilities, which have to be modeled more in detail with a simulation, in order to come up with the best network design possible.

Shahooei et al., 2019 introduces the concept of an underground freight transportation (UFT) system utilizing space beneath highways. This automated transportation system involves individual vehicles transporting freight through tunnels and pipelines between intermodal terminals. The research specifically focuses on enhancing corridor capacity between the Port of Houston and a terminal near Dallas. The paper develops operational equations for this system, including headway, capacity, and speed calculations, but doesn't test the design, as will be done in this research.

Visser et al., 2009 and Shin et al., 2018 conduct qualitative examinations of innovative transport solutions to connect ports and their hinterlands. The first one focuses on the Port of Rotterdam and evaluates automated Trucks and Multi Trailer Systems, Automated Trains, Automated Barge Handling Systems, and Automated Capsule/Alternative Rail Systems, already commented previously. Meanwhile, the latter presents a broader overview of various innovative transport systems, identifying standout contenders that could significantly influence logistics. One such contender is the Freight Shuttle System (FSS), an automated dual-directional electrical shuttle capable of transporting single container units at speeds of up to 112 km/h using Linear Induction Motors (LIMs). Similarly, the Electric Cargo Conveyor (ECCO) is discussed, sharing similarities with the maglev container transportation system under investigation in this research. Despite their theoretical foundations and lack of practical implementation, these systems hold significant potential, especially as effective connectors for shorter distances, linking hinterland terminals and seaports. This insight propels our research to develop and test a system layout accommodating maglev characteristics. The primary objective is to practically integrate this innovative solution into port logistics and assess its viability as a connector between seaports and dry ports, as well as for intra and inter-terminal transportation.

2.3. Conclusion

In this comprehensive background chapter, we have delved into two critical aspects: the analysis of current port operations and a literature review exploring diverse container port transportation methods. These findings provide the basis for the objective of designing the integration of an autonomous maglev cargo transportation system into the complex network of port logistics.

The analysis of current terminal operations has provided fundamental aspects for the design and integration of the maglev system within existing port structures. This investigation predominantly focused on automated and semi-automated terminals, as they represent the forefront of innovation in port operations. While each terminal has unique designs, we aimed to discern commonalities and general principles, so that the designed system maglev can be standardized and easily applicable to different terminals.

Throughout this analysis, we uncovered essential requirements for system design and performance enhancement, simultaneously identifying weaknesses and areas for improvement. These insights come together with the literature review findings, shaping a cohesive understanding of the challenges and opportunities that lie ahead.

Across intra-terminal transport, reviewed studies discuss many different handling equipment, and converged on a common goal, as well as in the operations analysis: optimizing handling equipment usage, terminal layout, and automation for efficient container transfers within terminals; highlight the importance of minimizing handling movements. In this research intra-terminal usage of maglev replaces the AGVs or other means of internal transportation, proposing a solution for integrating this same transportation mean for connecting to a dry port, which is not found in literature, and therefore generating a different terminal layout design.

Within inter-terminal transport (ITT) literature, it is emphasized the significance of streamlined connections between terminals, aiming to reduce vessel turnaround and dwell times. Simulation-based evaluations shed light on innovative systems that enhance overall terminal efficiency. In this paper we will delve into ITT in addition to the transportation between the seaport terminals and the dry port.

Seaport Terminals - Inland Terminals Transport discussions, spotlighted solutions bridging seaports and hinterlands. These studies highlighted the potential of innovation in improving intermodal connectivity, efficiency, and environmental impact. Research on similar systems for connecting to the hinterland, as the electric automated shuttles and ECCO maglev, is reviewed. However these only present qualitative analysis or the conceptual layout, without any quantitative research to test this one, unlike this research, in which we will make use of a simulation in order to assess its integration viability and practical considerations.

Therefore, this literature review underlines two significant gaps in the existing body of research, which will be tackled together in this research: the integration of a container transport system within the three distinct scopes of port logistics – intra-terminal, inter-terminal, and seaport-hinterland connections; and a comprehensive research on cargo maglev system integration into port operations. The potential significance of addressing this gap lies in the transformative impact that this setup with autonomous maglev cargo system can have on port logistics, making dry ports become a serious alternative for solving the capacity, congestion, efficiency and pollution issues of seaports and trucks. Moreover, none of these study quantitatively the direct connection of the dry port to the berth, without intermediate transport, for larger scales and volumes, analysing its possible integration and performance.

To address this gap, the proposed research will focus on designing a transportation network and port layout that seamlessly integrates the autonomous maglev system into different facets of port logistics - from inside terminal movements to inter-terminal connections and transportation to the hinterland terminal or dry port. Consequently, this research combines different scopes and characteristics of previously analyzed literature, bringing a unique and innovative layout and insights. Simulation-based methodologies will be employed to assess the feasibility, effectiveness, and operational dynamics of the proposed system within various contexts, using real-world data for its verification and validation.

Paper	**Transport system**	Intra-terminal transport layout design	Different equipment comparison	Storage strategies	Rail modeling	Costs analysis	Seaport ITT	Seaport terminals - inland terminals	**method**
Kim et al. (2012)	linear motor conveyance system (LMCS), AR/RS, overhead grid rail (GRAIL), SPEEDPORT, SuperDock, automated container system by ZPMC (ACS-ZPMC), and AUTOCON		x	x		x			Qualitative review
Liu, C.I. et al. (2002)	AGVs, linear motor conveyance system (LMCS), overhead grid rail system (GR), and high-rise automated storage and retrieval structure (AS/RS)	x	x	x		x			Terminal Design and simulation
Liu, C.I. et al. (2004)	AGV's	x							Terminal design and simulation
Xiangda , L. et al. (2021)	AGVs and ARMGs	x		x		x			Terminal Design and simulation
D'Ariano et al. (2018)	-	x			x				Terminal design and simulation
Duinkerken et al. (2006)	multi-trailer system (MTS), AGVs and automated lift vehicles (ALVs)		x			x	x		Simulation
Truong et al. (2020)	Automated wagon / monorail						x		Simulation
Hansen (2004)	Automated linear motor wagons	x			x			x	Case study process times analysis
Gattuso et al. (2018)	AGW (Automated Guided Wagon)	x			x			x	Network model
Rosa et al. (2009)	Automated rail shuttles	x						x	Case study Qualitative analysis and system design and port organizational analysis
Leriche et al. (2015)	Rail shuttle system				x		x	x	Design and simulation
Pourmohammad-Zia et al. (2020)	AGV platooning					x		x	Bi-objective MIP optimization
X. Wang et al. (2018)	AGVs							x	autoregressive integrated moving average (ARIMA) model
Shahooei et al. (2019)	Automated underground freight transportation (UFT)					x		x	Schematic design
Visser et al. (2009)	Auto. Trucks, MTS, Automated Trains, Auto. Barge Handling Systems, Auto. Capsule/alternative rail Systems						x	X	Qualitative analysis
Shin et al. (2018)	Autocon, Freight shuttle system (FSS), ECCO, cargo tram, cargo cap... (22)							X	Qualitative review
This research	**Automated maglev cargo shuttle**	x			X*		X	x	**Terminal & network Design and simulation**

Figure 2.8: Research gap sources coverage. X* means that the topic is treated but not modeled.

3

System design

3.1. TSB Cargo maglev system

In recent years, there has been a significant advancement in fully automated magnetic levitation (maglev) cargo shuttles, providing an innovative solution for container transportation within port logistics. In this study, we focus on the **Transport System Bögl (TSB) Cargo**, a cutting-edge maglev system specifically engineered for containerized freight transportation. Developed by the German company Max Bögl, the TSB Cargo system comprises both a passenger version and the Cargo version, which is the primary focus of our research. This system has undergone comprehensive development and testing, with operating demonstration tracks established in Sengenthal, Germany (860 meters), and Chengdu, China (3.5 kilometers). Presently, efforts are underway to implement the TSB Cargo system in real-world projects, marking a significant milestone in its journey from concept to practical application.

Figure 3.1: TSB Cargo, the maglev transport system from Max Bögl at the 860-meter test track in Sengenthal (Germany) . Source: Bögl, 2021.

Technical Specifications and Key Features

The TSB Cargo system boasts several impressive capabilities that can revolutionize port operations (Source: Bögl, 2021):

- **High Speed and Efficiency:** It can reach speeds of up to 150 kilometers per hour (km/h) while maintaining low energy consumption (see 3.2). The system boasts an acceleration rate of 1.3 meters per second squared (m/s^2).
- **Autonomy:** Individual containers travel autonomously, providing flexibility in scheduling and adapting to fluctuating demand.
- **Adaptable Infrastructure:** The system can operate on tracks with steeper gradients (up to 10%) and tighter curves (minimum horizontal radius of 45 meters) compared to traditional railways.
- **Environmental Benefits:** The TSB Cargo system contributes to a more sustainable port operation with minimal noise pollution and low CO_2 emissions.

- **Interaction with handling equipment:** The system allows to interact with cranes for loading and unloading container to and from the vehicle.

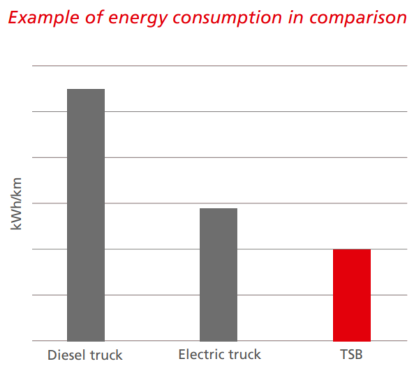

Figure 3.2: TSB energy consumption comparison to other transport systems. Due to the novelty of the system, exact values on emissions can't be given. Source: Bögl, 2021

Moreover, it is worth noting that vehicles operation requires a 20-second headway time (distance between vehicles). However, there is the possibility of digital coupling between vehicles, in order to increase their frequency, and therefore this assumption is used for this study.

Switching Mechanisms
The TSB Cargo system utilizes various switches to navigate the network (see Figure 3.3).

- X-switch
- Y-switch
- Slide switch

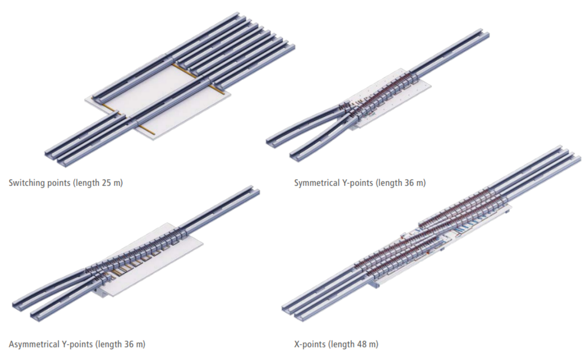

Figure 3.3: Different types of switches. Source: Bögl, 2021

Furthermore, it should be emphasized that the operation of vehicles necessitates a 20-second headway time (the distance between vehicles). However, digital coupling between vehicles is possible to enhance their frequency. Therefore, this assumption is employed for this study.

3.2. Port reference setting

The objective is to create a versatile design applicable to various port layouts. To establish a framework, a specific port structure and terminal setting have been selected as reference points for the design.

3.2.1. Port structure

The TSB guideway exhibits remarkable flexibility and can seamlessly adapt to diverse infrastructures. Consequently, its performance is minimally impacted by variations in berth shape, track configuration between terminals, or distances (except for marginal time increases). To establish a foundational design, we have chosen a straightforward reference setting that can be effortlessly adjusted to suit different environments. As illustrated in Figure 3.4, this setting comprises three container terminals (one being the main modelled terminal, and two external ones) and a barge terminal, all linked to the inland terminal. These terminals align along a linear berthline, each spaced 2 km apart. The barge terminal is situated near the river mouth, at 2 km from the coastline. For simplicity reasons it is assumed the dry port is located at a distance of 20km from each of the terminals.

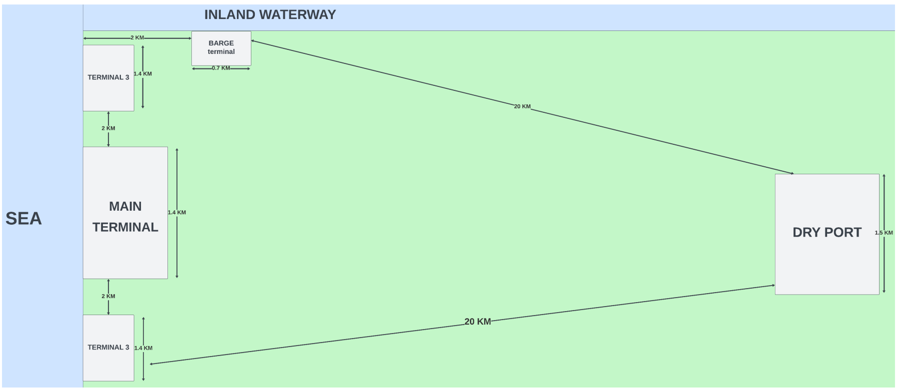

Figure 3.4: Port terminals reference setting

3.2.2. Terminal reference

The referenc terminal is based on terminal HHLA Container Terminal Altenwerder (CTA) of Hamburg (HHLA, 2023), from which the following data for design was retrieved:

- Terminal size : 1400x600m
- Number of berths: 4 (HPA, 2021)
- Quay cranes per berth : 15 gantry quay cranes - assumption taken for the design of four per berth
- Number of rails & size: 9x 720m
- Number of terminals of Port of Hamburg: 4 container terminals (CTA, Container Terminal Burchardkai - CTB, Container Terminal Tollerort - CTT, and EUROGATE)
- Storage blocks: 26 storage blocks - 260x24x13m
- Available handling equipment at current terminal yard: 2 RMGs per storage block, 52 in total.
- Actual yard storage design: Perpendicular storage blocks (see 3.6).

From the following information the following terminal setting reference is formed, depicted in Figure 3.5.

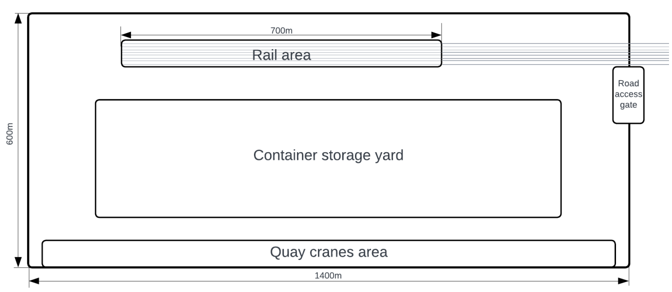

Figure 3.5: Standard terminal setup, based on CTA HHLA terminal (Hamburg).

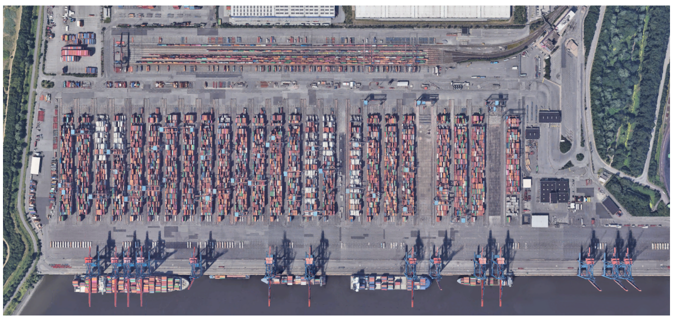

Figure 3.6: HHLA CTA Hamburg current terminal design. Source: Google Earth.

From the above described blocks size, the 1.6 conversion rate of TEU-to-container (40% 20ft and 60% 40ft containers, source: Consulting, 2022), containers sizes, and an average utilization of 80% (Jan Niklas Sikorra, 2021), leads to an operational estimated capacity of 1080 containers per block.

3.3. System network type selection

Within the aforementioned port and terminal context, various design options can be contemplated for the maglev system. This subsection will explore and discuss these alternatives, considering their respective merits, and ultimately identify the most viable choices. As mentioned earlier, the system needs to integrate intra-terminal operations within the seaport, inter-terminal transportation, and a connection to the dry port. It must effectively manage all these container movements, ensuring they are completed on time.

Figure 3.7 shows the different options considered for the connection between the dry port and the other four port terminals. These will be shortly analyzed below.

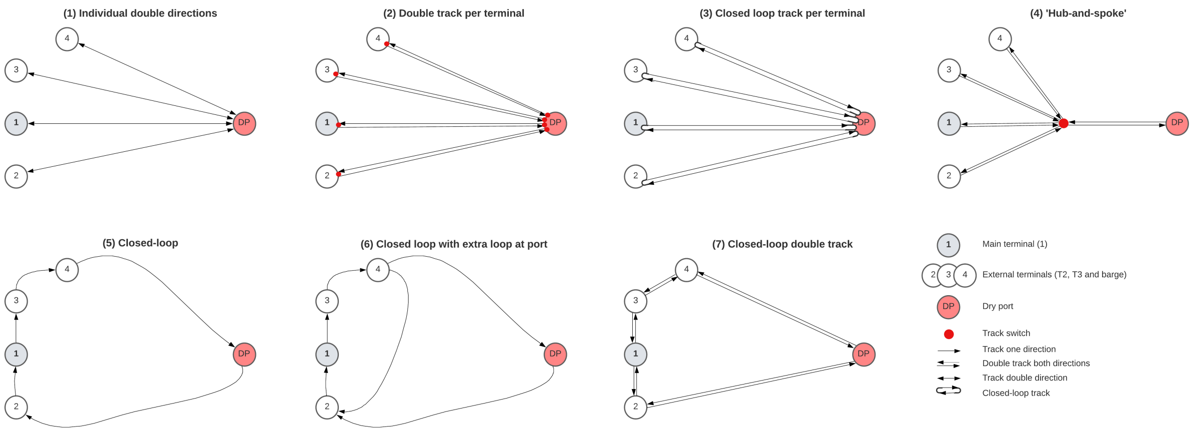

Figure 3.7: Different options for maglev network system design and the connections between the four port terminals and the dry port. Source: own design.

To evaluate the different proposed designs for the system, the weighted sum method approach was applied (Sabnis et al., 2024). This method was chosen because it allows for the aggregation of scores across multiple criteria, with each criterion weighted according to its importance. This approach therefore provides a comprehensive evaluation framework, enabling a systematic comparison to identify the most suitable alternative based on the combined weighted scores. The matrix is shown in Table 3.8. This matrix integrates six criteria, with each criterion assigned different weights based on its importance.

To assess the designs comprehensively, a questionnaire was circulated among field experts and members from various departments of the TSB maglev section. They were asked to provide scores ranging from 1 (poor) to 5 (excellent) for each design concerning specific criteria. The scores obtained from the questionnaire responses were then aggregated to construct the weighted decision matrix. Additionally, discussions were held with experts to determine the relative importance of each criterion in the decision-making process. These insights were crucial in assigning different weights to each criterion in the weighted decision matrix, and are discussed next.

Determining the weights, emphasis was heavily placed on the 'Capacity' criterion due to the research's objective of developing a standardized system adaptable to diverse port scenarios. A high capacity is imperative to ensure scalability across varying container volumes. It is crucial for the system's success, as investing in a new system that cannot handle the entire demand and necessitates the use of additional transport means would be counterproductive. Therefore, a fundamental requirement is that the system's capacity is sufficient to meet current demand without causing slowdowns or becoming a bottleneck in comparison to the current benchmark. Key cost indicators for the system include track length and the number of switches, with the former being the prominent, and therefore the reason of the high importance given. 'Total switches operation time' represents the pressure exerted on the switches, the frequency of their movements, and the time these movements consume—an essential criterion to prevent switches from becoming bottlenecks and reducing operational capacity. The distance the vehicles travel impacts system performance in terms of energy consumption and transit times. Lastly, the system's resilience, although important, is assigned a lower weight, considering that, as a new system, it is designed to minimize failures. In the event of a failure, the impact would be relatively similar for all the systems, justifying the lower weight assigned to this criterion. The possibility of further expansion of the system is not taken into account as a rating criteria as the implementation of this one would be very alike for all of them.

It is important to note that the designs of these systems are simplified versions intended to select which designs to further focus on for additional designing and testing with the simulation. Consequently, the scores provided are not precise, and are given through logic reasoning, as the final performance of each design is not fully known and will be determined after the simulation. This acknowledgment underscores the preliminary nature of the assessments made in this chapter and emphasizes the need for further evaluation and refinement in subsequent stages of the design process.

Criteria	Weight	Design 1	Design 2	Design 3	Design 4	Design 5	Design 6	Design 7
Capacity	5	1	4	4	3	4	4	5
Track length	4	4	1	1	3	5	4	2
Switches operations time	3	4	1	4	1	5	5	5
Vehicles driving distance	2	5	5	5	5	3	4	3
Nr. of switches	1	4	2	4	2	5	5	4
System resilience	1	2	4	4	3	2	3	5
total		**49**	**43**	**54**	**45**	**68**	**67**	**63**

Figure 3.8: Systems ratings. Score: 1 (poor) to 5(excellent).

Design 1 presents inherent limitations in capacity due to its single-track configuration with bidirectional traffic. Vehicles must wait for others to clear the track before proceeding in the opposite direction to avoid collisions, leading to potential congestion and reduced throughput. Whereas, designs 2 and 3 suffer from significant efficiency issues, both operationally and in terms of costs, primarily due to the elongated track caused by individual connections to the dry port per terminal, in addition to having a highly inefficient ITT. Design 4's complexity lies in the hub, where numerous tracks interact with the switches, potentially overwhelming them and creating a bottleneck, along with a more intricate infrastructure construction due to multiple crossings. As depicted in Table 3.8, the designs ranking highest are the 5th, 6th, and 7th, in this order. Consequently, these will undergo further design development and evaluation through simulation in the subsequent stages of this research. The three designs share similarities, with the 5th considered the standard or base system, holding the highest rank and thus receiving the utmost focus. With a total track length of around 50.9km, this system offers a high capacity, as it allows for continuous operation without the need for vehicles to wait for clearance or switch moves, resulting in uninterrupted flow outside of the terminals, and maximized throughput. Design 6 derives from the base system, introducing an additional connection between terminal 4 (barge terminal) and terminal 2, forming a closed-loop within the port, therefore avoiding unnecessary trips to the (relatively distant) dry port. The final design incorporates a double track throughout the entire closed-loop, providing a swift connection between terminals and reducing dependency on tracks for increased system resilience. While this enhances capacity significantly, it also incurs higher costs due to the extensive track distance covered.

The winning designs (5th, 6th and 7th) will from now on be treated as Design 1: Base Design, Design 2: Shortcut, and Design 3: Double track. These are further designed and explained in this chapter in sections 3.4, 3.5 and 3.6, respectively.

3.4. Base design - Design 1

This design is the base for all others, serving as the starting point for further adaptations. As a result, it is extensively discussed, with subsequent sections focusing on modifications specific to each design while referring back to this one as the standard.

The design of the maglev system in the terminal is based on three key design choices: the berth connection, the yard storage and the rail connection. Moreover, the design of the dry port terminal, and the track connection between this one and the dry port, are also treated in this section.

3.4.1. Berth connection

One of the primary drawbacks associated with current close dry ports (see 1.1 for explanation on the close dry port concept), which are generally linked to seaports by rail, is the frequent necessity of temporary storage upon arrival at the port due to the lack of flexibility and reliability of this mode. The requirement for temporary storage at the terminal, even if for a brief period, adds strain to the system, maintaining the same number of handling moves at the terminal but adding to the overall system, from arrival at the dry port to vessel loading, resulting in additional costs. Moreover, this practice does not offer significant advantages, as it does not substantially increase port terminal storage capacity. Additionally, containers often need to be delivered to the dry port well in advance of usual times, which is inconvenient for the shipper. Therefore, the objective of establishing a maglev technology connection between the dry port and seaport terminal is to create a seamless link with the berth, ensuring just-in-time container arrivals and direct loading or unloading onto the vessel, synchronized with the quay crane. This challenges the traditional approach to terminal operations, which typically involve intermediate storage. However, this deviation from the 'status quo' is necessary because there has not been a transport mode with the technical capabilities of this maglev system, which enables the rapid, individual, reliable transportation of a high volume of containers and efficient interaction with quay cranes, while being completely autonomous. Thus, as previously discussed, one of the objectives of this research is to demonstrate the feasibility of this direct connection.

In line with this requirement, the design of the maglev system involves TSB vehicles arriving at the assigned quay crane, coming to a stop, and awaiting container loading, unloading, or both sequentially. Subsequently, the vehicle proceeds to its next designated destination. The design, illustrated in Figure 3.9, incorporates two parallel tracks along the berth: one directly linked to the quay cranes and another designated for vehicles with destinations other than the terminal's berth, referred to as the 'fast track'. While the fast track is optional and could be omitted for ports with smaller volumes, it serves as a beneficial solution in high-volume ports, alleviating vehicle congestion at the berth. Additionally, in cases of persistent congestion at the berth, another alternative may be to add extra switches and connections between the two tracks throughout the berth length. This alternative constitutes Design 4, which is further developed and explained in section 3.7.

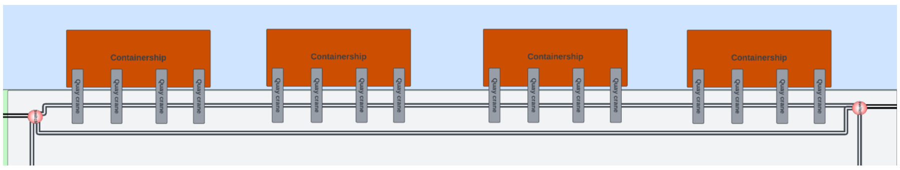

Figure 3.9: Berth connection track design. The red circles represent switches. The picture shows the containerships, quay cranes and TSB tracks by the berth.

3.4.2. Yard storage

Yard storage layouts are commonly categorized into two types: parallel and perpendicular (refer to Section 2.1.2). Among the crane types used in storage yards for stacking containers in blocks, the cantilever RMG is the suitable choice for (un)loading TSB vehicles. In this scenario, the TSB track runs parallel to the RMG rails, allowing the cantilever side of the crane to reach the vehicle. It's essential for the TSB track to align parallel with the stack; a perpendicular layout would obstruct the RMG's reach to the vehicle due to crossing with the maglev guideway. This constraint results in two feasible designs: the parallel and perpendicular layouts, illustrated in Figure 3.10.

It should be emphasized that the size and number of blocks, as well as the quantity of parallel tracks, can be adjusted based on terminal requirements, volumes and container dwell times, which will determine the specific required container storage capacity, as will be done in Chapter 4.

Upon comparison, the parallel layout emerges as the superior choice. The perpendicular layout necessitates multiple switches to interconnect numerous parallel tracks, along with additional total track length and the requirement for a larger space usage for guideway turns. These factors, combined with the time loss associated with switch movements, contribute to a design significantly less efficient than the parallel alternative. Consequently, the parallel yard layout is selected for the research design and subsequent testing through simulation.

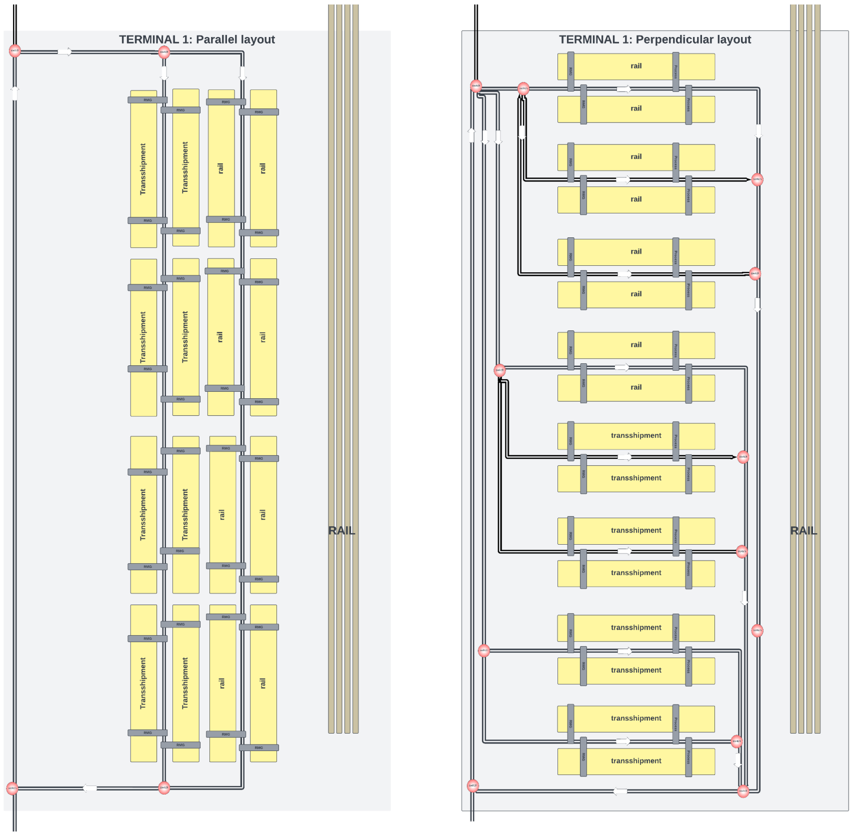

Figure 3.10: Parallel and perpendicular terminal yard layouts with TSB system integration. The red circles represent the switches.

Another design to be considered for evaluating its impact on the system involves a setup similar to this base one, but with the exclusion of TSB for intra-terminal transportation, specifically for rail and transshipment containers. This alternative constitutes Design 5, which is further developed and explained in section 3.8.

Note that in other figures from later designs, less detailed storage blocks setups might appear for clarity and simplification, however the storage block's setup will still be the described one, unless specified.

3.4.3. Rail connection

As highlighted previously, one of the challenges faced by terminals is the inefficiency of rail (un)loading operations, a concern amplified by the anticipated growth in the upcoming years, making it a focal point for terminal operations. The primary source of inefficiency typically arises from the additional handling moves required to transfer containers from the storage block to the railcar. As elucidated in Section 2.1.3, these movements involve: (1) loading the container with a crane into a transporter, (2) moving the container to the buffer space, and unloading the transporter with a rail crane to the predetermined buffer position; once the railcar arrives (3) cranes pick up the container from the buffer and load it onto the railcar.

Given the surplus space available in the terminal yard due to the relocation of approximately half of the storage volume to the dry port, the terminal yard has an opportunity to focus on rail container operations. Various solutions were explored alongside the TSB system design to minimize these handling moves. One option considered was placing rail storage directly adjacent to the rail tracks, utilizing the same cranes from the storage block to (un)load the railcars, thus eliminating the need for transport between these two locations. However, this proved unfeasible due to the strict predetermined positioning of containers on the railcar, known shortly before loading. As a result, this setup would entail a high number of repositioning moves if located nearby in the same block or extra transportation if moved to another block, making it inefficient.

Another considered approach involved introducing a parallel TSB track between the storage block and the rail, dedicated solely to positioning containers at the determined loading point onto the railcar. Nevertheless, the best solution still appears to be the use of lift Automated Guided Vehicles (AGVs) in combination with racks. Lift-AGVs can pick up and place containers on/from racks, where cranes later lift the container, eliminating the need for waiting time between the two processes. This system, employed at APM Terminal in Maasvlakte, Rotterdam (APM, 2023), as discussed in Section 2.1.3, is recommended for this terminal design. The advantage of simultaneously utilizing TSB and AGVs lies in their seamless cooperation, sharing the same cranes at the storage yard. These systems can operate independently, with cantilever RMGs placing or picking up containers on/from the racks when the TSBs are not present at the crane for operations. The proposed system, incorporating a sketch of the AGV route, is illustrated in Figure 3.11. Notably, the AGVs' route passes through the same area as the TSB guideway, but given the elevation of the latter, there is no interference, allowing AGVs to move beneath the tracks without issue. While this solution doesn't directly decrease the number of handling moves as intended, it does improve the efficiency of transportation. It achieves this by strategically storing rail containers close to the rail and optimizing the usage of lift-AGVs and rail RMGs through the utilization of racks. This approach minimizes waiting times and enhances overall operational efficiency.

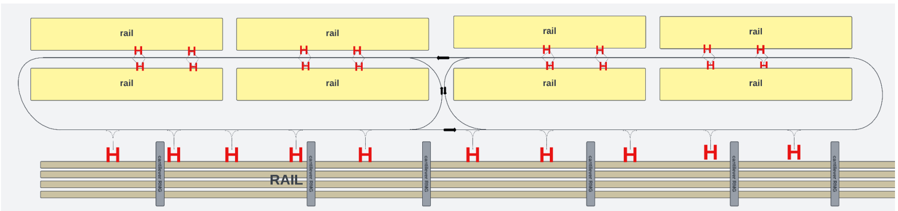

Figure 3.11: Design of the terminal yard system for connecting the rail to storage block. The AGVs pickup and drop container from and to the racks (depicted in red) and travel to their destination through the drawn route.

3.4.4. Dry port design

The (close) dry port serves as a crucial storage facility for containers arriving and departing to and from the hinterland via trucks. The terminal layout, depicted in Figure 3.12, is structured into distinct export and import sections, with containers segregated accordingly.

The design incorporates four parallel TSB tracks, each shared by four container blocks—two for export and two for import. Each storage block features a dedicated RMG for truck operations, along with an additional cantilever RMG crane specifically for TSB vehicle loading and unloading tasks. The movable RMGs are designed to overlap, facilitating simultaneous container handling from both sides.

Upon the TSB vehicle's arrival at the dry port, the system assesses the appropriate track based on the priority list of containers scheduled for vessel loading at the berth. If the TSB is transporting a container, it is unloaded in the 'import' area and stored accordingly. Subsequently, the vehicle proceeds to the export area to be loaded with another container destined for transfer to a different terminal.

Trucks accessing the terminal for container drop-off and pick-up utilize two entrance (and exit) gates—one for export and one for import containers. For export containers, trucks head to the unloading side adjacent to the designated export storage block, where an RMG crane lifts the container from the truck and positions it in storage. On the import loading side, RMGs retrieve the containers from storage, loading them onto the truck for departure.

It's important to note that the terminal's scalability allows for expansion by increasing the number of container blocks per track or adding more parallel tracks, with prioritization given to the former option. Additionally, besides its primary storage role, the dry port can accommodate customs functions and container repair services.

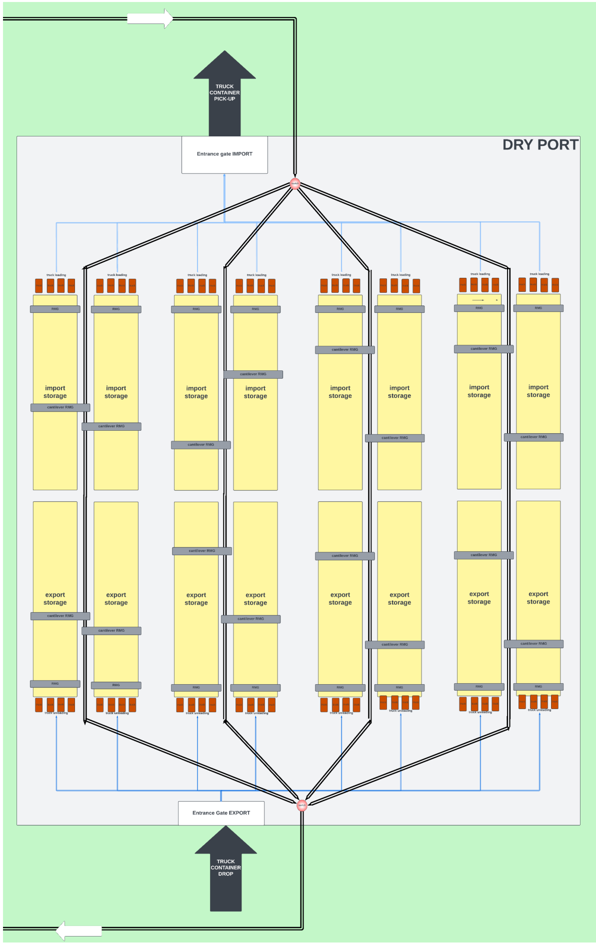

Figure 3.12: Dry port sketch design. Red circles represent switches, red rectangles trucks (un)loading locations and blue lines trucks path for getting to (un)loading locations.

Note that in other figures from later designs, less detailed storage blocks setups might appear for clarity and simplification, however the dry ports setup will still be the described one, unless specified.

3.4.5. Connection seaport - dry port

The connection between the seaport terminals and the dry port will be established through a one-direction closed-loop system, as discussed in Section 3.3. Although this was conceptualized in a circular layout, connecting the barge terminal to the dry port and then to terminal 2, in reality, the tracks will run parallel to each other.

This design choice is driven by two main factors. Firstly, it is more cost-effective to construct a double track than to build two single tracks separately. Secondly, it enhances system resilience. By positioning both tracks side by side, we can incorporate switches at the start and end of this approximately 20 km track. This setup enables the system to maintain operational continuity in the event of disruptions, such as vehicle malfunctions or power outages. If one track is affected, vehicles can still pass through the other track, ensuring the uninterrupted transportation of containers between the dry port and seaport terminals. For obvious reasons, this would reduce considerably the capacity, as there would only be one direction available. Consequently, if the track is open in one direction and there are TSBs passing, the vehicles traveling in the opposite direction would have to wait for these vehicles to pass, then change the switch and proceed themselves. The track will then appear as illustrated in Figure 3.13.

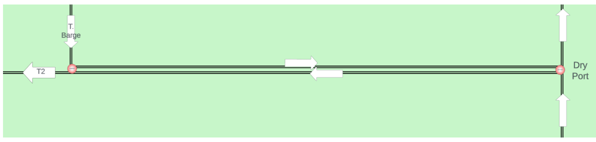

Figure 3.13: Track connecting the seaport (left) to the dry port (right). The distance from the port to the dry port is approximately 20km. Red circles indicate switches.

For clarity and visual representation, the track will be depicted in the rest of this study in circular form in the figures. However, in reality, it will follow the linear layout described above.

Regarding the resilience of the overall TSB system, in the event of disruptions at the port, the system could revert to operating in a double-directional mode. However, this would significantly reduce capacity, as all vehicles would need to synchronize to travel in the same direction.

3.4.6. Final Design 1

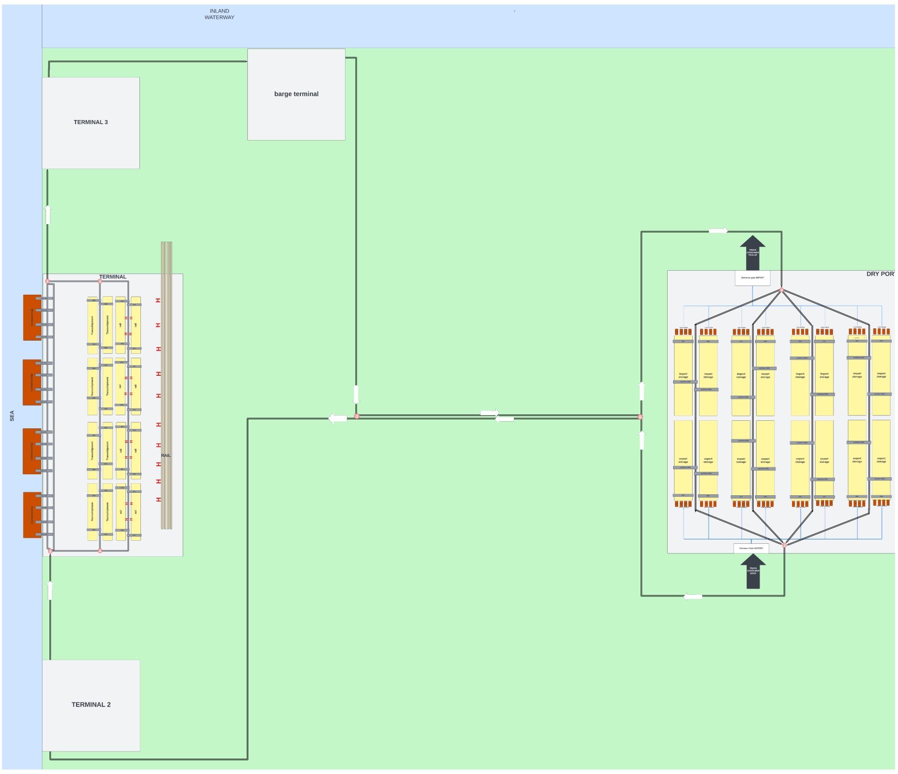

Figure 3.14: Full Design 1 sketch. Not in real scale.

3.5. Design 2: Shortcut connection around the port

Design 2, as presented in Figure 3.15, introduces a strategic shortcut track spanning approximately 8.9km, connecting the barge terminal directly to terminal 2. This addition aims to optimize the transportation route within the port logistics system. Specifically, the shortcut track serves as an efficient pathway for vehicles not requiring access to the dry port, offering a significant reduction in travel distance of approximately 31.2km (equivalent to around 13 minutes of travel time).

Primarily, the shortcut track serves as a crucial pathway for vehicles engaged in inter-terminal transfer (ITT) operations, facilitating swift transfers between various terminal pairs. These pairs include terminal 1 to terminal 2, terminal 3 to terminal 2, terminal 3 to terminal 1, and journeys originating from the barge terminal to any of the aforementioned terminals (1, 2, and 3). Additionally, the operational strategy encompasses the efficient utilization of the shortcut track by empty vehicles. This strategic approach aims to rectify import-export imbalances across container terminals by enabling empty vehicles departing from one terminal to traverse the shortcut track towards another terminal with a higher volume of import containers compared to export containers. For example, an empty vehicle departing from terminal 3 can exploit the shortcut track to reach terminal 2 during periods characterized by an excess unbalance of import containers at this terminal or when no containers are available at the dry port.

The implementation of Design 2 not only streamlines inter-terminal transportation but also enhances operational efficiency by effectively managing container flows and optimizing resource allocation within the port logistics system. Further analysis and simulation studies will provide insights into the performance and effectiveness of Design 2 in meeting the objectives of the port logistics infrastructure.

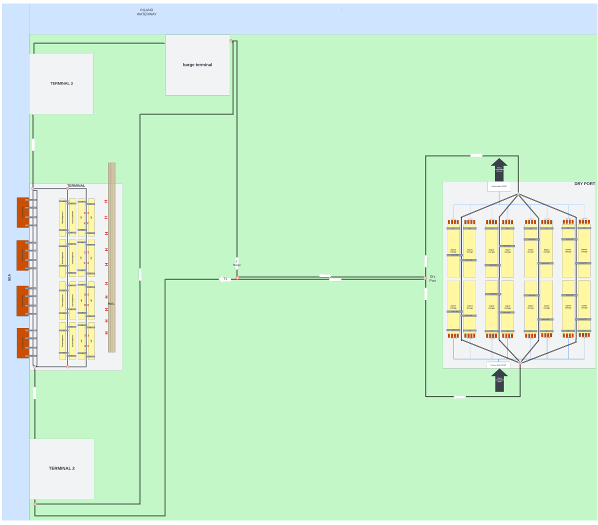

Figure 3.15: Shortcut track design. Red circles represent switches.

3.6. Design 3: Double track

After selecting the 7th network design in Section 3.3, this section delves into the detailed design process.

Initially, the network type appeared straightforward. However, upon closer examination during the detailed design phase, complexities emerged. One significant challenge arose from the handling of import containers at the quay crane, where the destination is unknown until the container is loaded onto the TSB from these cranes. This presents several complications:

- The quay crane may load the container onto a vehicle traveling in one direction, only for it to require transport in the opposite direction, negating the anticipated reduction in travel distance.
- Uncertainty regarding whether the container needs to be stored in the terminal yard necessitates connections from both tracks to the yard. Additionally, for ITT containers destined for another terminal, the vehicle must enter the yard to store the container.
- Balancing the number of vehicles on both tracks is essential. Therefore, provisions must be made for track-switching to re-balance vehicle distribution.

In light of these challenges, five alternative designs are presented, representative of all possibilities, and categorized into two groups: single-direction (where both tracks follow the same direction) and double-direction (where each track travels in opposite directions). The three alternatives in the first group and two in the second group will be briefly introduced in the following sections and subsequently evaluated to determine the optimal solution.

3.6.1. Single direction

The single-direction group of designs includes three alternatives: Design 1.1, Design 1.2, and Design 1.3.

Design 1.1 (depicted in Figure 3.16) features two parallel tracks running in the same direction throughout the system. Notable differences are observed at both the seaport terminal and the dry port. At the seaport terminal, each terminal is equipped with a 'Y' switch after the berth, connecting to the terminal yard to accommodate the storage of import containers. Subsequently, the two tracks merge into an 'X' switch before dividing into rail and transshipment tracks. Another 'X' switch, positioned after the yard, redirects vehicles back to the main tracks, with the system deciding whether to route them to track 1 or track 2 based on occupancy levels to balance the load.

Infrastructure at the dry port entails dividing the total number of dry port lanes by the two main tracks. For instance, in this illustration, the dry port features three tracks, with two accessed by track 1 (red) and one by track 2 (blue). Although an even number of tracks is ideal for system balance, this representation offers a simplified view.

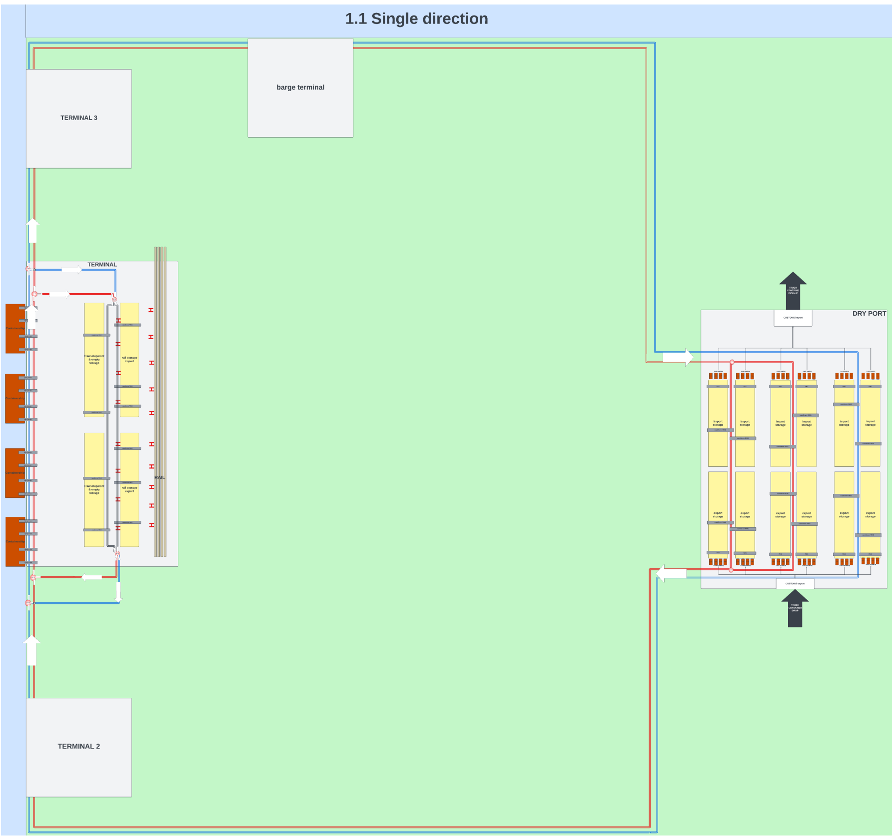

Figure 3.16: Double track - Single direction - 1.1 base sketch. Track 1 in red, track 2 in blue and shared tracks in black. Red circles represent switches and black circles at track intersections represent level changes.

Initially, the concept of double tracks aimed to reduce the distance traveled between terminals by allowing two-directional movement. However, in the context of single-direction designs, the inclusion of a shortcut track offers a solution to this objective. Therefore, Design 1.2 (Figure 3.17) ,closely resembles

Design 1.1, but incorporates a shortcut track between the barge terminal and T2, similar to Design 2. However, the connection to this shortcut is more complex, requiring three 'Y' switches and a level change on each side of the shortcut.

Design 1.3 (Figure 3.18) shares similarities with Design 1.1 and 1.2, also including the shortcut track, but features only one track to the dry port instead of two. As the tracks already run parallel to each other (as explained in subsection 3.4.5 , though not depicted as such for simplicity), an additional track for enhancing system resilience is deemed unnecessary. This approach reduces infrastructure complexity and cost, as it necessitates only an 'X' switch on each side of the shortcut track instead of three 'Y' switches and a level change.

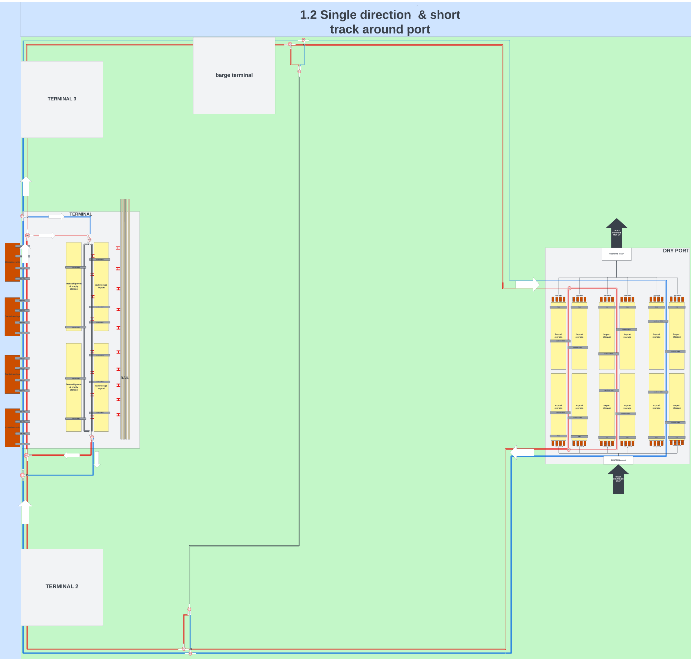

Figure 3.17: (1.2) Single direction & short track around port. Red circles represent switches and black circles at track intersections represent level changes.

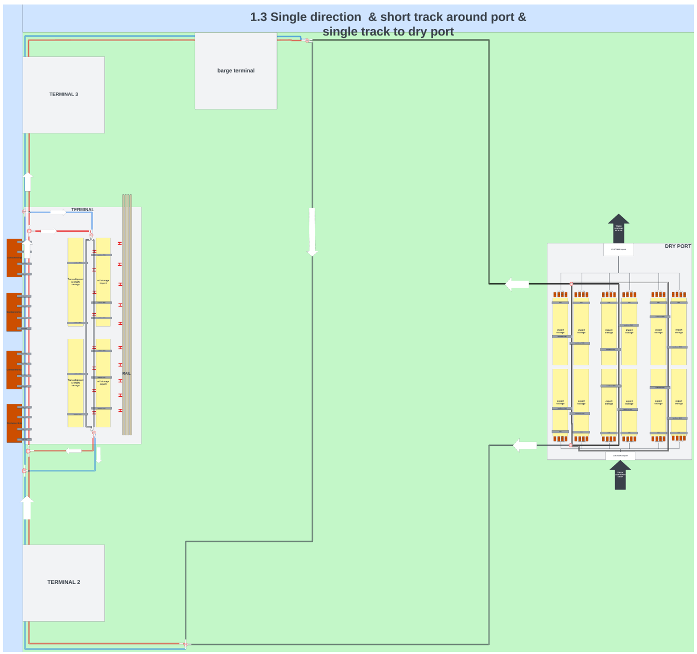

Figure 3.18: (1.3) Single direction & short track around port & single track to dry port. Red circles represent switches and black circles at track intersections represent level changes.

3.6.2. Double direction

In the context of two-direction designs for the double tracks, Figure 3.19 illustrates the base model (2.1). The key distinction between these designs and the single-direction variant lies in the increased complexity at the seaport terminal yard. With two directions, each track must be duplicated, requiring parallel tracks at the yard. Consequently, this design necessitates a total of 8 'Y' switches and 4 level changes per terminal. However, the double-direction setup loses its advantage when assuming that the quay crane does not select the track or vehicle to unload a container based on its destination, as this information is only known after loading onto the vehicle, potentially resulting in containers being sent in the opposite direction of their optimal route.

To address this issue, design 2.2 (Figure 3.20) introduces a sliding switch at the end of each berth track. This mechanism offers a solution by allowing a vehicle to use the switch after loading with a new container at the berth, enabling it to change to the other track and reverse directions. With this option, the sliding switch can be utilized by all vehicles requiring access to the terminal yard, simplifying the infrastructure requirements. Consequently, this design would only require the same infrastructure as Design 1 (Figure 3.4), supplemented with two additional sliding switches at the terminals. However, the use of sliding switches may lead to congestion at the terminal, as each vehicle requires adjustment, and the one-directional exit from the yard may create an imbalance in the number of vehicles on each track.

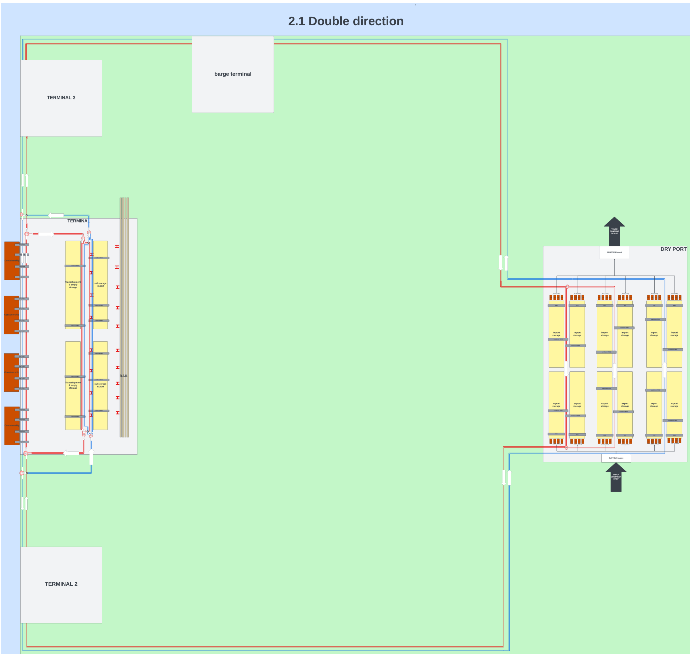

Figure 3.19: Double track - Double direction - (2.1) base sketch. Track 1 in red (clockwise direction) and track 2 in blue (counterclockwise direction). Red circles represent switches and black circles at track intersections represent level changes.

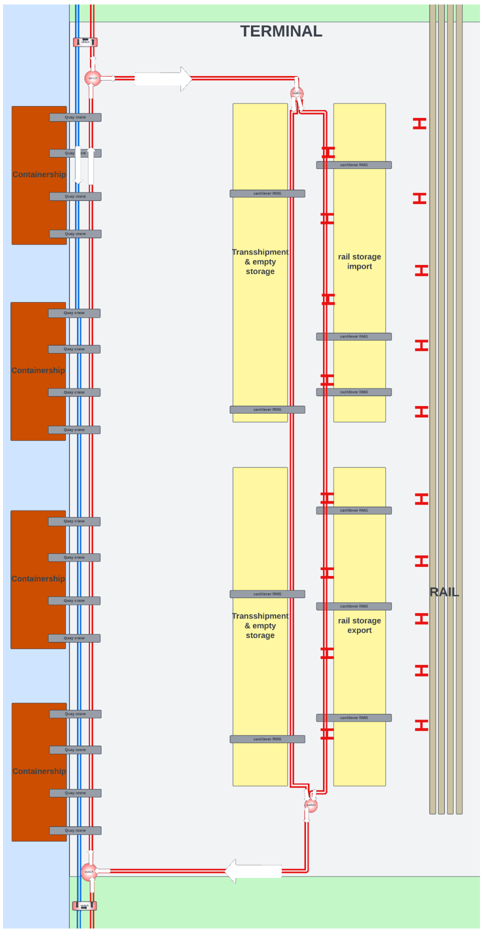

Figure 3.20: (2.2) Double direction with sliding switch. Track 1 in red (clockwise direction) and track 2 in blue (counterclockwise direction). Red circles represent switches ,black circles at track intersections represent level changes and red rectangles represent sliding switches.

3.6.3. Double track design selection & conclusion

A comparison of the five double-track alternatives is presented in Table 3.21, outlining the respective pros and cons of each design. After consultation with field experts from the TSB department of Max Bögl, **Design 1.3** (Figure 3.18) was selected as the preferred option due to its advantages and disadvantages outlined in the above table. It combines the benefits of increased capacity, shortcut tracks, and track-switching options from other designs. While it lacks the highest resilience due to the absence of double tracks at the terminal yard and to the dry port, its additional switches facilitate continued operations during disruptions between the port and dry port. Systems with greater expected resilience may encounter more bottlenecks and require more complex and costly infrastructure due to excessive switch usage. Hence, this design was selected for its balanced advantages without significant drawbacks.

The chosen design therefore features two tracks traveling in the same direction, incorporating a shortcut track and a single track to the dry port. As discussed earlier, this design aims to enhance system resilience while providing two tracks for TSB vehicles to be loaded and unloaded at the berth simultaneously, potentially improving berth operations performance. Further investigation into the effectiveness of this design will be conducted through simulation.

Double track design	Pros	Cons
Single direction designs		
1.1 - Single direction base	- Highly resilient - Higher scalability at dry port - Vehicles can change between tracks	- 2 extra Y switches - 2 Y switches converted to X switches - 2 level changes - Vehicles have to pass through the dry port
1.2 - Single direction & short track around port	- Increased capacity - Highly resilient - Higher scalability at dry port - Vehicles can change between tracks - Shorter covered distance (and time) by using the shortcut track	- 8 extra Y switches - 2 Y switches converted to X switches - 4 level changes - Many switches – higher waiting times - High infrastructure complexity - More kms of track
1.3 - Single direction & short track around port & single track to dry port	- Increased capacity - Vehicles can change between tracks - Shorter covered distance (and time) by using the shortcut track - Less switches - Less track kms - Vehicles can access all lanes at dry port	- 4 extra Y switches - 2 Y switches converted to X switches - 2 level changes
Double direction designs		
2.1 - Double direction base	- Highly (the most) resilient - Higher scalability at dry port	- 4 extra Y switches - 4 level changes - Vehicles have to pass through the dry port - Highly complex infrastructure at terminals - Vehicles number per track fixed
2.2 - Double direction with sliding switch	- Highly resilient - Higher scalability at dry port - Vehicles can change tracks - More simple infrastructure	- 2 extra sliding switches - Vehicles have to pass through the dry port - Highly reduced capacity because of congestion at sliding switches (>50% of vehicles have to use them)

Figure 3.21: Comparison table of the five double track alternative designs, with their pros and cons. Design 1.3 was selected as the preferred option.

3.7. Design 4: Extra switches at berth

The design enhancement introduced in Design 4: "Extra Switches at Berth," builds upon the foundational framework of Design 1 while incorporating modifications specifically at the berth tracks to mitigate congestion and improve operational efficiency. As depicted in Figure 3.22, this design augmentation entails the addition of three shortcut tracks, each approximately 140 meters in length, strategically connecting the fast track with the primary berth track. Notably, each of these three shortcut tracks integrates two extra switches, resulting in a total of six extra switches per terminal.

The primary function of these shortcut tracks is to facilitate smoother navigation for vehicles targeting berth spaces 2, 3, or 4. In scenarios where preceding berths are occupied by vehicles undergoing loading or unloading operations, the shortcut tracks offer an alternative route for vehicles to bypass congestion and facilitate their arrival at their designated berths. Consequently, this enables concurrent loading operations alongside ongoing activities at adjacent berths, thereby expecting an enhancement of overall berth utilization efficiency.

Each shortcut track, with its capacity to accommodate up to 10 TSB vehicles simultaneously, serves to alleviate potential congestion buildup on the fast track. Moreover, vehicles entering these shortcut tracks have the option to wait for vehicles passing through the primary berth track, either after completing their (un)loading operations or on route to berths further down the line. This strategic maneuver contributes to congestion mitigation efforts by optimizing traffic flow and minimizing potential bottlenecks.

Another similar design that was considered involved using 'X' switches instead of short connecting tracks. This design would have allowed bidirectional movement, enabling vehicles to pass from the berth to the fast track and vice versa. However, this option was not selected due to the potential for increased congestion. Implementing 'X' switches would have necessitated numerous switch adjustments at the berth, in addition to alignment with the paths of vehicles traversing the fast track. This added complexity could have resulted in heightened congestion levels, ultimately diminishing the efficiency gains intended by the design modification.

The efficacy of Design 4 will be evaluated through rigorous simulation studies to verify its effectiveness in reducing berth congestion and enhancing system productivity. The underlying hypothesis advances that by skipping queues at non-destination berths, vehicles can achieve improved operational efficiency. However, there exists uncertainty regarding the potential introduction of additional delays due to increased switch movements, alongside the associated costs of additional infrastructure deployment.

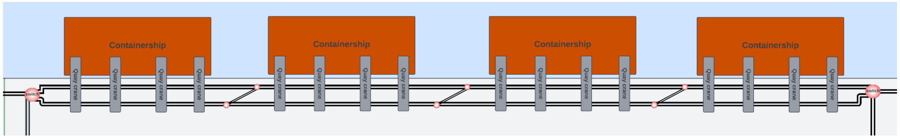

Figure 3.22: Tracks design for the extra 'Y' switches, and shortcuts added between the fast track and the berth track. Berth spaces 1 to 4, from left to right.

3.8. Design 5: Standard system without intra-terminal transport

Design 5 presents an alternative scenario where intra-terminal transportation tasks for rail and transshipment containers are excluded from the TSB system. Instead, Automated Guided Vehicles (AGVs) are employed to handle these operations, a practice commonly observed in many automated container terminals. In this setup, AGVs navigate beneath the maglev tracks and engage in the loading and unloading of containers with the quay cranes during intervals when TSB vehicles are not in operation. However, it's important to note that inter-terminal transportation (ITT) and transportation to the dry port for road containers remain the responsibility of the TSB system.

The rationale behind this design is to explore a phased implementation approach for the TSB system, particularly suitable for initial deployment at a port, with lower volumes assined to TSB. This approach allows for gradual testing and scaling up of the TSB system over time. Additionally, with this setup, not all road transport needs to be redirected to the dry port immediately, and a share of traditional truck-based container handling could still continue at the terminal.

The challenge with this design arises from the fact that, as discussed in earlier designs, the quay crane lacks information about the destination of import containers, which is just known once picking up the container and later loading it into the vehicle. Consequently, when the quay crane picks up a container, it doesn't know whether it should be loaded onto a TSB or an AGV. Unlike the other designs, in this scenario, we must assume that the quay crane selects the container based on the available transport mode (TSB or AGV). There are two potential approaches to address this issue: assuming the capability of the quay crane to identify the correct container from the vessel; or using dual-trolley quay cranes, which count with an intermediate "buffer" storage, which would then enable the QC to select the correct container from there.

To accommodate the TSB system's connection to terminal storage for dropping ITT containers, a small storage area with an RMG crane is situated adjacent to the berth track, as depictued in Figure 3.23 . This facilitates the unloading of containers arriving from other terminals and their placement into storage. An alternative consideration was positioning this storage area next to the fast track instead of the berth track. However, this option was discarded due to concerns about exacerbating the imbalance between export and import volumes. Placing the storage area at the fast track would result in TSB vehicles unloading containers and leaving the terminal directly, without loading import containers from vessels, thereby worsening the export-import volume discrepancy.

Aside from the inclusion of the ITT storage area and the removal of terminal yard-related infrastructure, the rest of the system design remains unchanged. The modeling and integration of the AGV system in collaboration with the TSB system will be discussed further in the Chapter 4.

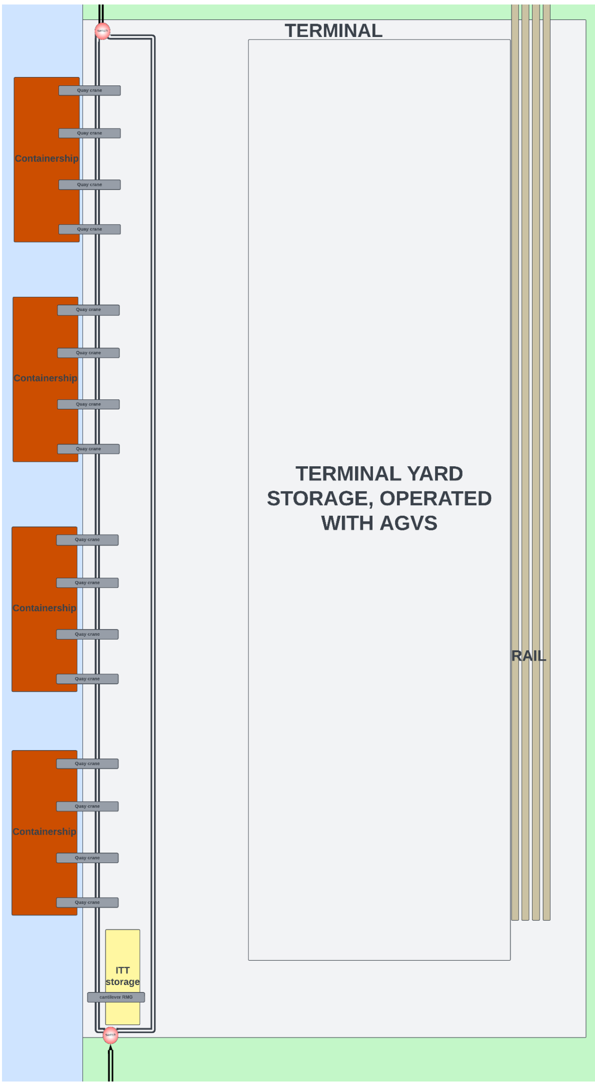

Figure 3.23: Terminal layout without intra-terminal transport performed by TSB.

3.9. Conclusion

In conclusion, this chapter has introduced five distinct designs to optimize the Transport System Bögl (TSB) within port logistics: the base design, shortcut design, double track design, extra switches at berth, and design without intra-terminal transport. Each design offers unique features and trade-offs, addressing specific challenges in port operations.

The next chapter (4) will discuss the modeling of these designs for simulation, followed by performance and scenario testing in Chapter 5. Through simulation experiments, we will assess the effectiveness of each design in meeting key performance metrics and optimizing port logistics.

In summary, the exploration of these designs provides valuable insights into enhancing TSB system integration within port operations. By systematically evaluating these designs, we aim to inform decision-making and optimize TSB systems for real-world applications.

4 Simulation

Simulation plays a crucial role in evaluating port logistics systems by providing a virtual environment to analyze complex operations, identify bottlenecks, and test different scenarios. In this chapter, we present a simulation model developed using Siemens Tecnomatix Plant Simulation software (version 2201) to study the performance of the five different designs presented in the previous section (see Figure 4.1 for Design 1's simulation model).

Simulation enables stakeholders to assess the performance of port logistics systems under various conditions, without the need for costly and time-consuming real-world experiments. By simulating different scenarios, decision-makers can make informed choices to improve efficiency, reduce costs, and enhance overall operations. It serves as a valuable tool for strategic planning, capacity optimization, and risk management in port terminals.

This chapter encompasses various sections, including Key Performance Indicators (KPIs) for performance evaluation (4.1), assumptions & parameters defining model characteristics (4.2), input data, simulation modeling & operational rules for system components (4.4), extra designs modifications (4.5), and validation & verification processes (4.6).

4.1. KPIs

The KPIs (Key Performance Indicators) in the simulation model are crucial metrics used to assess the performance and effectiveness of the TSB system, in connection to the rest of the port. These include:

- Vessels Berth Times: Calculate the average and median times vessels spend at the berth, providing insights into the efficiency of vessel operations, including loading and unloading processes. This is considered the most important KPI.
- Utilization of Vehicles: This group of KPIs encompasses the share of time vehicles spend traveling, waiting, at external terminals, and empty. It also includes the covered distance in kilometers and the average number of container moves per vehicle.
- Utilization of Handling Equipment: This set of KPIs evaluates the working time percentage and moves per hour for handling equipment, including Quay Cranes (QCs), Yard RMGs, and Dry Port RMGs.
- Total System Handled Volumes: This assesses the total volumes handled , testing its capacity.
- Volumes Stability: This has the slope index as the KPI to identify volume buildup trends over time, helping to proactively manage terminal operations and ensure stability in cargo volumes.
- Real-time Volumes per Terminal: This group of KPIs tracks the volumes to be handled in real-time across all terminals throughout the simulation period, ensuring balanced and even distribution of cargo volumes among terminals. This is named as 'volumes to be handled', as once the container is ready to be handled it is added to the indicator, which goal is to be minimized, handling containers as fast as possible, in order to minimize vessel berth times.

Figure 4.1: Picture of the full system simulation model from Plant Simulation. The three terminals can be seem above (T2, T1 and T3, in that order), the barge terminal on the right and the Dry port at the bottom. The thin grey lines are the TSB tracks. Vehicles go on clockwise direction.

These KPIs collectively provide a comprehensive framework for evaluating the efficiency, performance, and utilization of the TSB system within the port terminal simulation model.

4.2. Assumptions & parameters

Assumptions:

- Quay Cranes (QCs) lack information on import containers, with container destinations known only upon loading onto the TSB.
- The entire port's container demand volume is handled by the TSB.
- Loading and unloading order of containers is disregarded.
- Import containers are assigned to the four QCs of the berth, while export containers do not have an assigned QC.
- TSB loading operations function on a double cycling loading basis, allowing QCs to unload the TSB and load a new import container.
- The distance between the barge terminal and the dry port (DP) and between DP and Terminal 2 (T2) is assumed to be 20km.
- Priority is given to vessels that arrive earlier, eliminating other type of priority distinctions.
- Road containers are dropped off and picked up by trucks at the dry port.
- Rail containers are stored upon the rail cars' arrival on rail storage blocks by a separate system, lift-AGVs. Same the other way around, upon rail car arrival the lift-AGVs pickup the containers from the rail storage and take them to the railside.
- The lift-AGVs and trucks dont interfere in the RMGs operation with the TSB system.
- Containers arriving by barges are available at the barge terminal for subsequent transportation to the corresponding terminal.
- All containers are available at their corresponding storage once the vessel berths.

Parameters:

- Loading time for QCs (Tang et al., 2020) :
  - Single cycle: 105 seconds

- Double cycle: 160 seconds

- Loading time for RMGs (Saanen and Valkengoed, 2005):
  - Single cycle: 90 seconds
  - Double cycle: 140 seconds (assumption)
- Speed of TSB: 150 km/h (Bögl, 2021)
- Acceleration of TSB: 1.3 m/s² (Bögl, 2021)
- Buffer times for external terminals (explained in section 4.4.6).

4.3. Input data

Terminal's input data for the simulation is based on data from HHLA three Hamburg terminals (HHLA, 2022) and Hamburg port four container terminals container aggregate data on volumes, modal share, transshipments, empty containers and vessel calls (of Hamburg HPA, 2023b , of Hamburg HPA, 2023a & of Hamburg HPA, 2023c).

General Hamburg container terminal aggregate data volumes year 2022:

- Total volume: 8.3M TEUs (6.396M for the 3 HHLA terminals)
- export 49.4%
- import 50.6%
- Transshipment containers: 34.9%
  - on this transshipment share, inter-terminal transport containers are assumed to be 5%
- Share container hinterland traffic per mode
  - road: 47.3%
  - rail: 50.5%
  - barge: 2.2%

As there is no data available for inter-terminal transportation (ITT). it was assumed that from the total transshipment share, 5% was dedicated to these moves.
Therefore the total share per mode or category is the following, depicted in Figure 4.2.

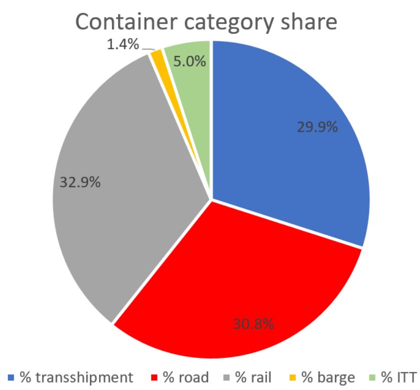

Figure 4.2: Container category share.

Assuming the CTA terminal handles 40% of the total 3 HHLA terminals in Hamburg (6.396 million in 2022), this equates to 2.558.400 TEUs annually. Using a conversion factor of 1.6 for passing from TEUs to containers (source: Consulting, 2022), this translates to 133,250 containers per month. Aligning the number of vessel calls in 2020 with the demand in 2022 results in an average of 80 monthly vessel calls. The dataset was compiled for a month-long vessel schedule, featuring volumes ranging from 422 to 7096 containers per vessel. The 80 vessel arrivals are distributed across the 30 days of the month, with 2 or 3 vessel arrivals per day, as illustrated in Figure 4.4. Additionally, the vessel arrival and volume schedules for T2 and T3 are depicted in Figure 4.5, showcasing a mirrored schedule between T2 and T3, where days 1-15 of T2 correspond to days 15-30 of T3, and vice versa.

Moreover, the vessel schedule for day 30 was added before day 1 as a warm-up period, and the vessel schedule from day 1 was extended to day 31 as a cool-down period. This ensures that the simulation adequately captures any initial transitory effects before day 1 and allows for a smooth conclusion in case the simulation extends beyond day 30. No additional days were included for warm-up and cool-down periods beyond day 30, as the system does not anticipate building up and the simulation is not expected to extend beyond day 31.

per month	total	road	rail	barge	ITT	transshipments
Total containers handled	133,250	41,006	43,780	1,907	6,663	39,895
import container handled	67,428	20,864	22,275	970	3,372	19,947
export container handled	65,822	20,142	21,504	937	3,292	19,947
nr vessels	80	30.77%	32.85%	1.43%	5.00%	29.94%

Figure 4.3: Summarized input data terminal 1

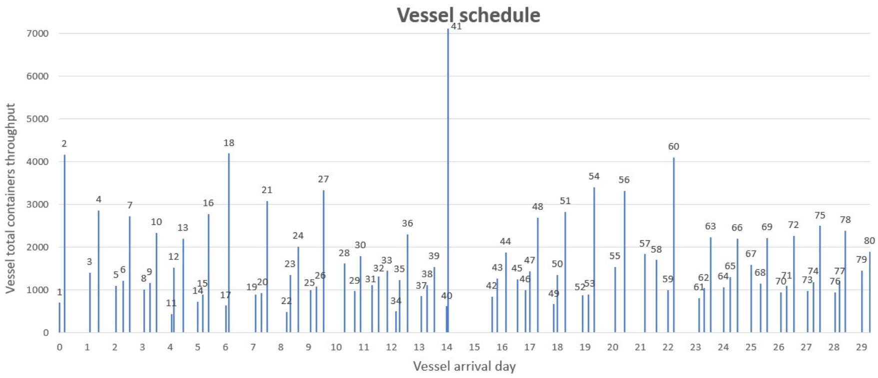

Figure 4.4: Terminal 1 monthly vessel schedule input, total throughput and the vessel arrival time. The data label indicates the vessel number.

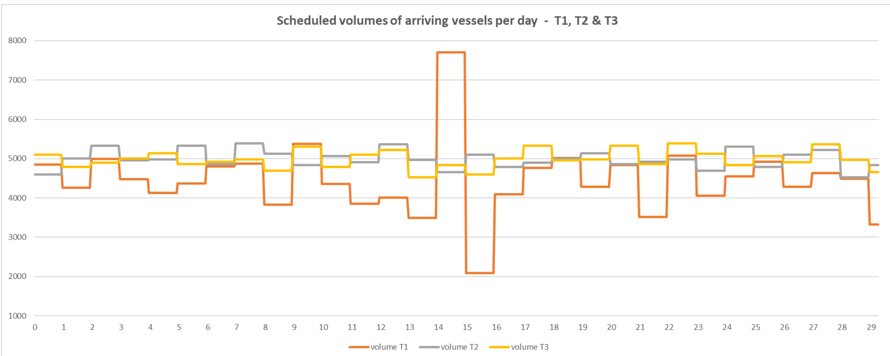

Figure 4.5: Scheduled volumes of arriving vessels per day - T1, T2 & T3.

Furthermore, with regards to container dwell times at the port of Hamburg, a report by Beacon, 2023 indicates an average dwell time of 3.3 days. However, when it comes to transshipment containers, there are no clear estimates. Raballand et al., 2012 suggests a transshipment time ranging between 5 and 10 days. For the purposes of this research, we have chosen to use an estimate of 6 days for transshipment container dwell times.

4.3.1. Design success definition

Based on the presented KPIs and input data, the success of the designs will be defined based on the following criteria:

- Meeting Container Demand on Time (requirement): The system must handle all container demand from the three terminals within the specified time frame. The maximum allowable schedule end time is set at one day after the last scheduled vessel's arrival, which in this case is **day 30.75**.
- Preventing Container Buildup (requirement): It is imperative that containers do not accumulate within the system, as this would indicate inefficiencies and potential delays. The input schedule has a slight slope index of -11.5. To allow for some margin, the maximum slope index accepted is **0**. Any value higher than this will be considered excessive inventory buildup.
- Improving Vessel's Median Berth Time (objective): The designs should aim to improve upon the benchmark median berth time for containerships in Germany, which stands at **18.96 hours** (source: UNCTAD, 2019). Achieving a lower median berth time would signify enhanced operational efficiency and performance.

As outlined in Section 4.1, various other Key Performance Indicators (KPIs) are analyzed for each design and scenario. However, the ones mentioned are the primary indicators that determine its success.

4.4. Simulation Modeling & Operational Rules for System Components

Figure 4.6 depicts the simulation model events graph, encompasses various agent groups, including trucks, rail lift-AGVs, vessels, quay cranes, vehicles (TSBs), container export, and container import. Trucks and rail lift-AGVs agents, highlighted in blue, are not directly integrated into the simulation model due to their low impact on the results, as they aren't closely linked to the TSB system. However, these agents' events are still mapped in the figure for providing a general view of the whole system's processes relationships. Moreover, container import and export groups serve as connectors between agents, however these are passive agents, awaiting loading or unloading without taking independent actions or decisions. TSB vehicles, the primary agents, interact with all other groups, except for AGVs and trucks, as explained.

This section delves into the simulation's components, elucidating scheduling, assignment rules, and algorithms, some of which are highlighted in the events graph with red markings. The algorithms are presented as rules for simplified explanation. This one is analyzed for the model of Design 1 which is the base for all of the others, for which their adaptations and differences will be treated in next Section 4.5. The section is structured into various components: general components, vessels, quay cranes, seaport terminal yard, dry port, and external terminals.

General components overview common elements across the system, such as the input datasets, switch operations and algorithms for assigning empty vehicle destinations. The quay cranes interaction, terminal yard, and dry port are part of the vehicle agent group but are delineated into distinct groups for clarity of explanation. External terminals, although treated as a black box, are explicated separately to elucidate their functioning. Therefore, note that vessels, quay cranes and seaport terminal yard subsection explanations are only for T1.

4.4.1. General components

This section comprises the explanation of some general features that are shared by all of the other systems: the input datasets, switch operation and the empty vehicles assignment.

Input datasets

The input datasets consist of three distinct sets: T1 vessels schedule, T1 import containers, and the remaining containers dataset. The following data is defined for each:

- T1 vessels schedule: vessels arrival time, import and export volume.

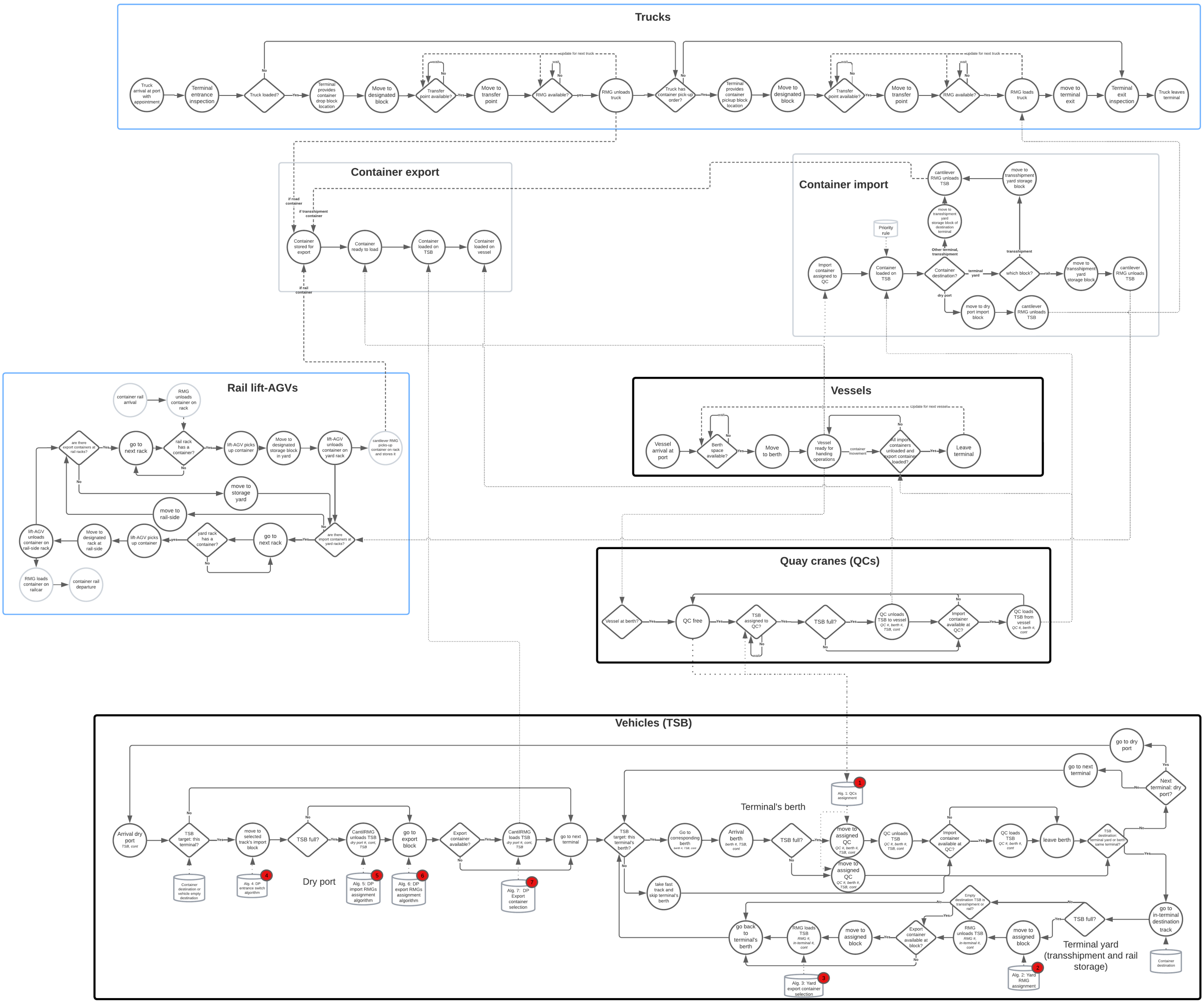

Figure 4.6: Events graph. Blue boxes represent the non-modelled agents, grey boxes the passive objects. Red circles indicate the algorithm used, with its assigned number.

- T1 import containers: container number, vessel number, arrival time (same as vessel arrival time), origin (all berth T1) and destination.
- Rest of containers dataset contains similar information as the previous one, encompassing all containers (import and export) for T2 and T3, as well as export T1 containers. The arrival times for these containers coincide with the respective vessels' arrivals. The origins for these containers vary, including the dry port, barge terminal, T1 rail storage, T1 transshipment storage, and T2 berth for arriving vessels.

The export arrival times are synchronized with the vessel arrival times because, in this research, storage volume is not a determining factor. The primary focus is on minimizing the volumes of containers to be handled, which encompasses when the vessel arrives at the port. Therefore, export arrival times are aligned with vessel arrivals to capture this aspect effectively.
For containers bound for T2 and T3, they are immediately placed into storage upon arrival at their defined origins. However, for T1 containers, they are placed on a buffer storage due to the possibility that the vessel's arrival time does not necessarily correspond to its berthing time, especially if all berth spaces are occupied.

Switch operation
In the simulation, the operation of switches is modeled based on several scenarios to accurately represent their real-world functionality. Here's how the operation of switches is simulated:

1. **Switch in the Required Position**: If the switch is already in the correct position for the approaching vehicle's destination, the vehicle can pass through without any delay.
2. **Switch in a Different Destination Position**: If the switch is set to a different destination than the one the vehicle intends to go, but the origin positions match, the vehicle must stop. It waits for 15 seconds, allowing time for the switch to be adjusted to the correct position. Once the switch is adjusted, the vehicle can proceed.
3. **Switch in a Different Origin Position with No Other Vehicles**: If the switch is set to a different origin position, but there are no vehicles present on the other origin track, the vehicle waits for 15 seconds while the switch is adjusted to align with its path. Once the adjustment is complete, the vehicle can continue its journey.
4. **Switch in a Different Origin Position with Other Vehicles Present**: If the switch is set to a different origin position and there are vehicles on the other origin track (at the last 150-300m from the switch, depending on the track), the approaching vehicle must wait until the other vehicles have passed the switch. Once the last 200m of the track before the switch is clear, the switch begins to adjust. The vehicle waits for 15 seconds while the adjustment takes place. After the switch is correctly positioned, the vehicle proceeds with its journey.

Empty vehicle assignment
In the empty vehicles assignment process, an algorithm is employed to determine the destination for each empty vehicle. The potential destinations include: (1) Terminal 1 berth, (2) dry port, (3) rail T1 yard, (4) transshipment T1 yard, (5) barge terminal, (6) Terminal 2, and (7) Terminal 3.

The algorithm selects the destination for the empty vehicle based on the terminal with the highest volume of export containers for the oldest vessel at berth. If none of the terminals have containers for this vessel, the empty vehicle is assigned to Terminal 3 if import containers are available; otherwise, Terminal 2, and last the barge terminal is considered. Terminal 3 is prioritized over Terminal 2 due to the latter's proximity to the dry port, which results in a higher influx of empty vehicles. This approach aims to maintain balance among the terminals.

While this algorithm appears to favor Terminal 1 in reducing vessel berth times, which are exclusively calculated for Terminal 1, an additional algorithm is activated when an empty vehicle arrives at the switch before Terminal 2 (see Section 4.4.6). This algorithm updates terminal statuses and performs a new assignment of the empty vehicle's destination, thereby ensuring equitable distribution among all three terminals.

4.4.2. Vessels

Upon arrival at the port, as defined by the vessel schedule dataset, vessels are assigned to a berth space if one is available; otherwise, they wait in the vessel waiting buffer. Berth spaces are allocated starting from berth space 4, followed by 3, 2, or 1, depending on availability. If all spaces are occupied, the vessel remains in the waiting buffer until a berth space becomes free.

Once berthed, export containers are moved from buffer storage to their respective origin locations, marked as 'ready to load'. Import containers are then assigned to each of the quay cranes at the vessel's berth for unloading.

The KPI 'containers to be handled' increases upon the vessel's arrival, reflecting the new total load to be handled, including both export and import containers. This KPI decreases as containers are processed, either loaded onto the vessel or stored at their designated destination locations.

Once all import containers are unloaded and all export containers are loaded onto the vessel, it departs, freeing up the berth space for incoming vessels.

4.4.3. Quay Cranes

Terminal 1 is currently modelled with 4 berths, with 4 quay cranes (QCs) each, based on the CTA Hamburg terminal data, as explained in Section 3.2. Quay cranes for each berth space are number from 4 to 1 from left to right.

Upon vehicles' arrival at Terminal 1, they encounter a switch. If a vehicle carries an export container destined for a vessel at Terminal 1, or if it is an empty vehicle with Terminal 1 berth as its destination, it is directed to the berth track. Conversely, if a vehicle is loaded with an Inter-Terminal Transfer (ITT) container bound for Terminal 1, it is directed to the fast track, with plans to switch to the yard track subsequently. Additionally, vehicles carrying containers destined for other terminals, or empty vehicles bound for other terminals, are also directed to the fast track.

This section will be further subdivided into subsections, beginning with the assignment of vehicles to quay cranes as they pass through the berth track, followed by an explanation of quay crane operations. Lastly, the operation of the 'X' switch after the respective tracks will be discussed.

Algorithm 1: QCs assignment

When a loaded TSB vehicle arrives at its designated berth, particularly at QC4, an assignment algorithm is initiated. This algorithm considers several factors:

- The number of TSB vehicles awaiting assignment prior to the vessel's berth.
- Availability of import containers at each quay crane (QC)
- Whether the QC already has a TSB already assigned or not

Only one TSB can be assigned at a time for QC3 and QC4. However, QC2 and QC1 can receive an additional TSB assignment if the QC is already in the process of loading the TSB vehicle, indicating that space will soon become available. Indeed, this allocation strategy aims to maintain a balanced distribution of vehicle assignments across all quay cranes. By considering the progression of the TSB from QC4 to QC1 or QC2 when it is nearing completion, the algorithm anticipates potential imbalances. Without this anticipation, the short distance to QC3 and QC4 would lead to underutilization of these quay cranes, decreasing the average number of QCs occupied simultaneously. Thus, by proactively assigning TSB vehicles to QCs based on their progression, the system can optimize the utilization of all available resources and ensure efficient operations throughout the terminal

If there are fewer than 4 vehicles waiting for assignment, the algorithm identifies the QC with the highest number of import containers. The TSB vehicle is then assigned to the furthest available QC space, with a maximum difference of 4 import containers compared to the QC with the most import containers. If no such QC is available, the vehicle is assigned to the furthest available QC with remaining import containers.

This algorithm aims to balance the volume of containers to be unloaded among all QCs. Without this balance, there is a risk of over-assigning QCs such as QC1 and QC2, leading to having a high rate of remaining import containers at QC3 and QC4, creating later inefficiencies due to empty trips and single cycles.

However, if there are 4 or more vehicles awaiting assignment in the berth space, or if no more import containers are available at any QC, the vehicle is simply assigned to the furthest available QC (in priority order: QC1, QC2, QC3, and QC4) to prevent excessive congestion at the berth.

The assignment process for empty vehicles differs slightly. When an empty vehicle passes by QC4, it may be assigned to the berth and subsequently to a QC, or it may pass through if the berth space is not suitable. The vehicle is assigned to the berth if it corresponds to the berth of the oldest vessel, or if the vessel is nearly finished loading export containers (>90%) and there are still more import containers than export containers remaining. If the berth space is beyond that of the oldest vessel, the vehicle is also assigned to the berth. Subsequently, the vehicle is assigned to QCs with remaining import containers, following a similar process as for loaded TSBs.

QC operations

Once the vehicle is assigned to a QC, the operation of this one involves several key tasks aimed at efficiently handling containers on and off the vessels. Upon detecting a fully loaded TSB vehicle with an export container, the quay crane initiates the process of picking up the container and loading it onto the vessel. after loading this export container into the vessel, if there are remaining import containers allocated to that specific QC, the quay crane proceeds to pick up an import container and loads it onto the TSB. In case of the TSB vehicle arriving empty the QC would just skip the first step.

Once the TSB vehicle has been fully unloaded and loaded, it is ready to depart from the berth. In cases where there are no remaining import containers to be processed, the empty vehicle will depart as soon as it has been unloaded. Additionally, after each movement by the quay crane, a check is performed to determine if the vessel is ready to depart. This readiness is signaled by the completion of unloading all import containers and loading all export containers onto the vessel. Upon the vessel's departure, a new vessel will occupy its berth space, initiating the cycle anew.

Switch after berth

The operation of the 'X' switch at the end of the berth track and fast track at T1 involves several conditional movements based on the status and destination of the vehicles. Specifically:

1. If a vehicle is carrying a container destined for the terminal yard (either rail or transshipment) or is empty with its destination set to one of these yard locations, then the destination is set to the yard track.
2. In cases where a vehicle is empty and there are vessels still present at Terminal 1 (T1), but no further T1 containers are available at the dry port, the vehicle stays at the terminal, directed to the yard track.
3. Otherwise, if none of the above conditions apply, the vehicle is directed to the track leading out of the terminal, toward Terminal 3 (T3).

4.4.4. Seaport terminal yard

In the terminal yard, there are five dedicated storage blocks for each, rail and transshipment containers, with each block being equipped with a crane (see Figure 4.7). As explained in 3.2, it is assumed each storage block has an strategic maximum capacity of 1080 containers. Based on the demand data and

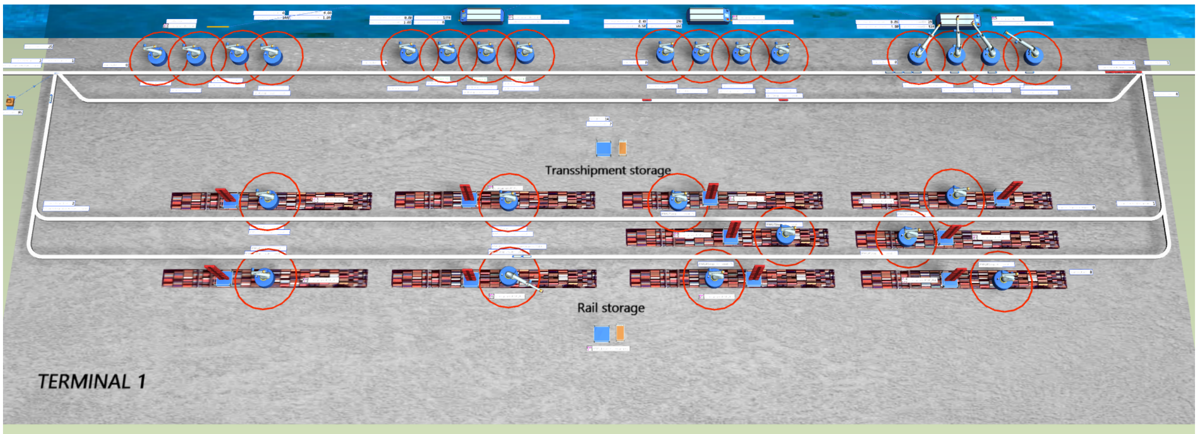

Figure 4.7: Picture of terminal 1, from the simulation model from Plant Simulation. The 4 berth spaces, 3 vessels, 16 QCs, the storage yard and the tracks can be seen.

dwell time estimations, rail needs an storage average of 4,815 containers and transshipment 4,750. Therefore, a minimum of five storage blocks are needed for each of them.

Vehicles entering the yard encounter a switch that directs them to either the rail or transshipment storage track, depending on the nature of their cargo or empty destination.
If a vehicle is loaded with an import container destined for either rail or transshipment, it will be directed to the corresponding storage track. Conversely, if the vehicle is empty, it will be assigned to the track corresponding to its designated empty destination. If no specific empty destination is specified, the vehicle will be assigned to the track with more containers to be handled. However, if there are already more than four vehicles waiting on that track, the empty vehicle will be assigned to the other track to balance the workload.

Upon passing the switch and arriving at the first storage block, an algorithm is executed to assign the yard RMG (Rail Mounted Gantry) crane responsible for unloading and loading containers for the vehicle, as described in the following subsection.

Algorithm 2: Yard RMG assignment
The assignment of yard RMGs (Rail Mounted Gantry cranes) is determined based on various factors depending on the status of the vehicles and containers in the storage blocks:

1. If a vehicle is loaded and there are more than three vehicles waiting or there are no export containers left for the oldest vessel, it is assigned to the furthest available RMG that still has export containers. If all RMGs are empty, it is assigned to the furthest available free RMG.
2. If a vehicle is loaded and there are more than three vehicles waiting or there are less than eight export containers left from the oldest vessel, it is assigned to the furthest available RMG that still has export containers for the oldest vessel. If all RMGs are empty, it is assigned to the furthest available RMG with export containers. If no RMGs have containers for the oldest vessel, it is assigned to the furthest available RMG.
3. For empty vehicles and other scenarios, the vehicle is assigned to the furthest available RMG that has a maximum of five fewer export containers for the oldest vessel than the storage block with the most of them. If no such RMGs are available, it is assigned to the furthest available RMG with containers for the oldest vessel. If no RMGs have containers for the oldest vessel, empty vehicles may proceed directly to the berth to assist with unloading processes, balancing the import-export discrepancy.

Additionally, if the oldest vessel has completed loading all its export containers but still has import containers to unload, vehicles may pass through the terminal empty to expedite the unloading process and reduce berth time. Empty vehicles arriving before reaching the yard will bypass the assignment process, while loaded vehicles will first unload their containers before proceeding empty to the oldest vessel at the berth.

Algorithm 3: Yard export container selection
The algorithm for selecting export containers from the terminal yard for loading onto the TSBs is determined based on several criteria:

- Time Berthed: Priority is given to containers for the vessel that has been berthed for the longest duration.
- Number of Waiting TSBs: The algorithm considers the number of TSBs waiting at each berth space.
- Availability of Containers: Containers available in the storage block for each vessel are assessed.
- Availability at Dry Port: Containers for the oldest vessel at the dry port are also considered. If containers are available for the oldest vessel at the dry port, they are prioritized to reduce congestion at the berth.

The algorithm prioritization is therefore as follows:

1. If the storage block has export containers for the oldest vessel and the number of TSBs waiting at its berth is less than the maximum specified (2 if containers are available at the dry port for the oldest vessel, and 4 otherwise), a container for this vessel is selected from the block.
2. If no containers are available for the oldest vessel or the maximum waiting TSB limit is reached, the algorithm moves to the second oldest vessel, provided it has fewer than 4 TSBs waiting at its berth.
3. If neither of the above conditions is met, the algorithm searches for the berth located just before the oldest vessel (e.g., if the oldest vessel is in berth space 4, then berth space 3) and sends a container if there are fewer than 3 TSBs waiting. This process continues iteratively, decrementing the berth space number each time, as long as there is a vessel at that berth space and export containers are available in the storage block for that vessel.

If no vessels are available at the berths or all available containers are exhausted, containers are sent for the oldest vessel regardless of the number of waiting TSBs at its berth.

4.4.5. Dry port

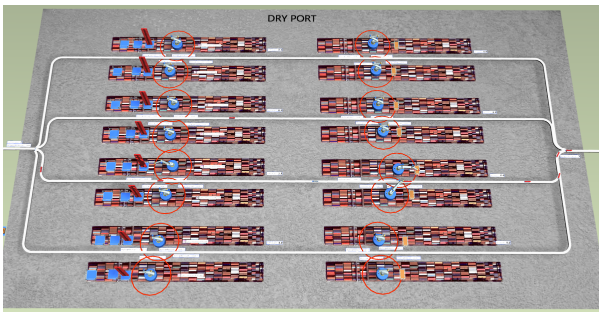

Figure 4.8: Picture of the Dry port terminal, from the simulation model in Plant Simulation. The 4 lanes can be seen, with the export blocks on the left and import blocks on the right. Vehicles follow a clockwise direction, entering thought the seitch at the right side.

The Dry port process is divided in the four different subsections explained next: the entrance switch, the assignment to the import RMG, the assignment to the export RMGs and the export container selection algorithms. The dry port layout, illustrated in Figure 4.8, is designed to accommodate both road import and export containers. Considering the demand data and estimated dwell times, the average storage capacity for road import containers is approximately 7,452 units, while export containers average around 7,181 units. To meet this demand, a minimum of seven container blocks is required, each with a capacity of 1,080 containers. However, to maintain operational balance between tracks, the design includes eight container blocks.

Algorithm 4: DP entrance switch algorithm
Upon arrival at the entrance switch of the dry port, the algorithm for selecting one of the four tracks is initiated. This decision is based on several factors including the current number of vehicles in each track, the time required to move the switch, and the volume of containers to be sent to the seaport terminals in each direction.

The algorithm performs the following steps in the presented order:

1. **Calculation of Expected Times**: The algorithm calculates the expected time for each track based on the number of vehicles on the export side, the number of vehicles on the import side, and an additional 15 seconds if the switch is not positioned in the direction of that track. This time calculation helps estimate the waiting time for each track.
2. **Selection of Shortest Time Lane**: If the TSB vehicle is loaded with a container destined for another terminal, it selects the lane with the shortest expected time.
3. **Availability of Export Containers**: The algorithm checks for each lane if there are export containers available in at least one of the export storage blocks. If no export containers are available in a lane, that lane is ruled out unless none of them have export containers left.
4. **Prioritization Based on Export Containers**: If all tracks have the same expected time, the algorithm chooses the track with the most export containers from the oldest vessel at Terminal 1. Alternatively, if the quantity of export containers for one lane exceeds the average of the other three plus 10, then, the vehicle is directly assigned to that lane.
5. **Comparison with Expected Times**: The algorithm compares the expected time for each track and makes the following decisions:
   - If the switch is in the track's position and the expected time for that track is lower than the expected times of all other tracks minus 180 seconds, then that track is selected.
   - If the expected time is lower than the expected times of all other tracks with available export containers, then that track is selected.
   - Otherwise, the vehicle moves to the track for which the switch is open.

By considering these factors, the algorithm efficiently selects the optimal track for the TSB vehicle at the entrance switch of the dry port.

Algorithm 5: DP import RMGs assignment algorithm
Upon passing the switch to its assigned track, if the vehicle is loaded with a dry port import container, it undergoes the import RMG assignment process. In this process, there are two cranes designated for import operations. These cranes can move parallel to the track and unload the vehicle at any location, overlapping each other. However, in this simplified model, there are four possible stops, with two for each crane (Stop1 - Crane 1, Stop2 - Crane 2, Stop3 - Crane 1, Stop4 - Crane 2, with Stop 1 being the furthest stop from the entrance).

The assignment process for the import RMGs is straightforward. The vehicle is assigned to the furthest available crane, ensuring efficient unloading of import containers from the vehicle.

Algorithm 6: DP export RMGs assignment algorithm
The export blocks, cranes, and stops are organized in the same manner as for import, with Stop1 - Crane 1, Stop2 - Crane 2, Stop3 - Crane 1, and Stop4 - Crane 2.

# at berth	85	90	95	100
1 vessel	17	18	19	20
2 vessels	23	24	26	27
3 vessels	27	29	30	32
4 vessels	29	31	33	34

Figure 4.9: Example maximum number of TSBs for T1 (maxNrTSBsT1) for different total number of TSB settings and for the base demand of 30% T1 volume.

Upon passing the import storage and arriving at the first export stop, if the TSB vehicle is empty, it undergoes assignment to an export stop according to the following criteria:

- Upon arrival at Stop 4: If there are export containers in storage 2 (from crane 2) and Stop 3 is occupied, the vehicle is assigned to Stop 4. Otherwise, the vehicle continues to the next stop continues.
- At Stop 3: If storage 1 still has export containers and Stop 2 is occupied, the vehicle is assigned to Stop 4. Otherwise, the vehicle continues to the next stop.
- At Stop 2: If storage 2 has export containers and Stop 1 is occupied, or if storage 2 has more containers than storage 1, then the vehicle is assigned to Stop 2, otherwise move to Stop 1.
- At Stop 1: If there are export containers available, the vehicle is assigned to Stop 1.

Algorithm 7: DP Export container selection
In order to select the container to load on the TSB, there is an assignment algorithm running, which will be based on the following:

- Number of vehicles at Terminal 1 (T1) and those heading towards T1.
- Import containers available at Terminal 2 (T2) and Terminal 3 (T3).
- Last sent container destination and the number of containers sent consecutively to that destination.
- Availability of export containers for T1, T2, and T3.

One of the key considerations for container selection is the number of vehicles at Terminal 1 (T1) or heading towards T1. This factor is crucial for maintaining balanced operations to avoid excessive congestion or overly extended berth times. Therefore, a maximum number of vehicles are specified depending on the number of vessels present at T1, along with the share of the total volume that corresponds to T1 and the total number of TSB vehicles in the system. The formula for determining the maximum number of vehicles (maxNrTSBsT1) is as follows:

- For 1 vessel: (share (%) of T1 volume / 1.54) * Number of TSBs
- For 2 vessels: (share (%) of T1 volume / 1.14) * Number of TSBs
- For 3 vessels: (share (%) of T1 volume / 0.97) * Number of TSBs
- For 4 vessels: (share (%) of T1 volume / 0.9) * Number of TSBs

Note that the result is rounded to an integer. The factor used in this formula was determined through extensive simulation testing to find an optimal value that balances operations across the three terminals. We will refer to the result of this calculation as the variable maxNrTSBsT1 from now on. See Figure4.9 for an example.

Then, the container selection algorithm would be as follows:

1. If the oldest vessel at T1 has no more export containers available at the yard and has containers at the assigned RMG's storage, load a container for T1's oldest vessel.
2. If there is at least one vessel at T1, there are T1 containers available, and TSBs at T1 + 0.5* vehicles going towards T1 ≤ maxNrTSBsT1, and vehicles going towards T1 ≤ 16 , then send a T1 container.
    - Select the vessel container based on their berth time, prioritizing the oldest vessel.

- If there has been more than 4 containers sent in a row to the same vessel, then select the next vessel.

3. If the vehicles for T1 exceed the maximum, then send containers to T2 or T3, prioritizing the terminal for which there are more containers available. If there has been 6 containers in a row sent to the same terminal, then send to the other one to avoid overcrowding.

This algorithm ensures efficient and balanced container selection based on various factors, including vessel arrivals, terminal capacities, and TSB availability, thereby optimizing overall terminal operations.

4.4.6. External Terminals

The external terminals (T2, T3, and barge terminal) are modeled as black boxes, as previously explained. This means there is an inflow and outflow of containers, but the internal processes are not explicitly modeled. Vessels are not simulated, but there is an object that stores all the import containers upon their arrival time as specified in the input dataset. Likewise, there is a drain where export containers are sent, simulating their loading onto vessels.
Upon arrival at the terminal, TSBs encounter a switch, which will be elaborated on next, directing them either to the berth or to the fast track. If they proceed to the fast track, they simply follow their path without any additional actions. However, if they are directed to the berth track, they enter the "black box," where the loading and unloading of containers occur, along with the internal transport operations for storing and loading rail and transshipment containers, as well as handling ITT containers arriving from other terminals. To simulate the time spent inside the terminal, a buffer time is added to every TSB vehicle entering the terminal, which will be further explained in the second subsection below.

Algorithm 8: External terminals switches
Before each external terminal, there is a switch that determines whether the vehicle moves to the berth track or the fast track. This works under the following rules:

- If the vehicle carries an export container destined for this external terminal, it moves to the berth track.
- If the vehicle carries a container for another destination, it moves to the fast track.
- If the vehicle is empty and the switch is at T3 or at the barge terminal, it moves to the berth track.
- If the vehicle is empty and the switch is at T2:

    1. If there is at least one vessel at T1, and there are no more containers for T1 at the dry port, and the total number of TSBs at T1 plus half the incoming ones is below 12, it moves to the fast track for later going to T1, assigning it as the new empty destination.
    2. If the first condition is not met and there are fewer import containers for T2 than for T3, it moves to the berth track.
    3. If there are more import containers at T3, it moves to the fast track for later going to T3, assigning it as the new empty destination.

This last assignment rule aims to prevent prolonged vessel loading times at T1. If there are no more export containers at the dry port for T1, it implies that no more vehicles are entering T1. If vehicles inside T1 get loaded with containers for different destinations and leave the terminal, there might be a reduced number of vehicles, leading to prolonged vessel loading times. Therefore, vehicles are directed to T1 to continue operations.

Furthermore, the assignment to T3 instead of T2, in case there are more import containers, helps reduce the imbalance between export and import containers. Without empty vehicles entering, the only vehicles entering are through export containers, leading to an imbalance that would continue to increase over time due to the higher rate of import containers.

External terminals Buffer time
As previously mentioned, vehicles entering the terminal are subjected to buffer time to simulate the duration they would spend at the terminal if it were modeled. This buffer time includes the time for all container exchanges between the yard and berth.

The buffer time assumptions are as follows:

- These assumptions are based on the premise of a perfectly operating terminal, without delays or congestion.
- There is a 62.67% probability that the import container loaded from the vessel is destined for the terminal yard (based on the input demand data).
- Considering the speed and acceleration of the TSB from the berth to the yard, stopping at a crane, unloading the container, getting loaded with a new one, and returning to the berth takes 230 seconds. Additionally, it takes 160 seconds to complete the double cycle operation by the QCs. Therefore, assuming perfect operation without congestion, a complete tour takes 7 minutes (420 seconds). Following these rules and based on the probability of doing a certain number of trips to the yard in a row, the determined buffer time is 13.50 minutes per TSB entering the external terminal.

Therefore, based on this:

- If the vehicle arrives loaded, the buffer time is 770.5 seconds.
- If the vehicle is empty, the buffer time is 715.5 seconds (770.5 - 55 seconds of difference between double cycle and single cycle).

However, when unloading, a new algorithm is executed to check the state of TSB vehicles at T1 for the empty vehicles at the switch. If there is at least one vessel at T1, and there are no more containers for T1 at the dry port, and the total number of TSBs at T1 plus half the incoming ones is below 12, the container will be unloaded, and then the vehicle leaves empty towards T1. In this case, the buffer time will be only 30 seconds, which is the time the QC takes to pick up the container, as the TSB can leave before the QC actually loads it onto the vessel.

Barge terminals do not require such buffer time as there is no intra-terminal transportation. Therefore, vehicles only perform loading and unloading operations before leaving. The buffer times are:

- Unload and load container: 160 seconds
- Only unload container: 30 seconds
- If the vehicle is empty and gets loaded: 105 seconds

	p	t (s)	t (m)
load container and leave terminal	0.373	160	2.7
1 yard tour	0.234	550	9.2
2 yard tour	0.147	940	15.7
3 yard tour	0.092	1330	22.2
4 yard tour	0.058	1720	28.7
5 yard tour	0.036	2110	35.2
6 yard tour	0.023	2500	41.7
7 yard tour	0.014	2890	48.2
8 yard tour	0.009	3280	54.7
9 yard tour	0.006	3670	61.2
total sum (p*t)		**770.518**	**12.84**

Figure 4.10: Calculation buffer time external terminals. The number of full tours around the terminal probability multiplied by the total time of this.

4.5. Extra Designs

This sections goes through the model adaptations that were made for each different design, taking as a basis the Design 1 model explained in earlier sections of the chapter.

4.5.1. Design 2: Shortcut connection around the port

As described in Section 3.5, the only addition to the base design is the shortcut track connecting the barge terminal and Terminal 2. Therefore, in the model, this 8.9 km track is added. Additionally, the 'Y' switch of the barge terminal exit and the 'Y' switch of Terminal 2's entrance had to be changed to 'X' switches, as there are now two entrances and two exits for each.

The 'X' switch at Terminal 2's entrance operates under the same algorithm as described in subsection 4.4.6, dividing the incoming vehicles from the two tracks to the berth track and the fast track. However, the operation of the barge terminal switch differs, as it now has to choose whether to assign a vehicle to the shortcut track towards T2 or continue in the direction of the dry port. This follows the following rule: only go to the dry port destination track if:

- The TSB is empty, and its empty destination is the dry port.
- The TSB vehicle is loaded, and the container destination is the dry port.

For the rest of the cases, take the shortcut track. It is worth noting that the dry port destination comprises the highest share of vehicles, as the ITT share and empty vehicle share are very reduced compared to the number of vehicles loaded with an import container for road pickup.

4.5.2. Design 3: Double track

As described in Section 3.6 , the differences between this design and Design 1 are as follows:

- Two parallel tracks extend over the entire port length (from Terminal 2 to the barge terminal), instead of a single track with fast tracks at the terminals. Quay cranes can simultaneously load vehicles on the two tracks.
- The shortcut connecting the barge terminal and Terminal 2, as in Design 2.
- Each track has its connection to the terminal yard (see Figure ...), and the 'Y' switches at the yard are changed to 'X' switches.

Due to these changes, there are a few assignment rules that have been modified and will be discussed below. The assignment of vehicles to the quay cranes is adapted, and the rule at the yard exit switch to decide which track to route the TSB vehicle to is adjusted. Moreover, as there are no fast-tracks at the terminals, it means that all the vehicles passing through the external terminals, even if not being destined to those, could also experience delays due to congestion while other vehicles are loading. Therefore, the buffer times are adapted and explained in one of the subsections below. Moreover the maximum number of TSBs to T1 is also adjusted and discussed below.

Double track QCs assignment

The rule for assigning vehicles to QCs for the double track design is similar to the main design, with some slight differences. First, this algorithm is processed when the TSB vehicle arrives at QC4 on any of the two tracks, instead of just one. Second, the algorithm follows the same rules, but instead of checking whether a certain QC stop is available, it checks if both stops (one on each track) are available. Then, if neither of the two stops is free for any of the QCs, it will select the QC that is available on its corresponding track.

For the rest of the algorithm, as mentioned, it is the same as the main design. It also considers the number of waiting vehicles for the berth across the two tracks and compares the remaining import containers of the four cranes to determine the optimal assignment.

After yard switch: track assignment

With the implementation of the double track design, the two parallel tracks now serve the same function. Previously, external vehicles would take the fast track, while vehicles destined for the terminal's berth would take the berth track. However, with the new design, the switches that have two different destinations (Track 1 or Track 2) must choose between them.

The selection at the switch after the terminal yard will be based on the number of vehicles present at Track 1 and Track 2 of T1's berth track. The switch will select the track with the lower number of vehicles to balance the load and decrease congestion, thereby increasing the efficiency of loading operations.

Similarly, at the 'X' switch before T2, this decision must be made between Track 1 and Track 2. The same approach will be followed, comparing the number of vehicles at Track 1 and Track 2 between the switch and the exit of Terminal 1.

Double track external terminal's buffer times
In the double track design, without the presence of fast tracks, vehicles not destined for a specific terminal may experience delays. To accommodate this, the buffer times for external terminals are adjusted as follows:

- For vehicles destined to the specific terminal, the buffer time remains unchanged.
- For vehicles not destined for the specific terminal:
  - If the buffer of the specific track has at least one vehicle, a buffer time of 160 seconds is applied. This corresponds to the loading double cycle time that the vehicles in front will incur.
  - If the buffer at the track is free, it indicates no congestion, and therefore the vehicle will not enter the buffer.

Adaptation max number of TSBs sent to T1
Do to the increased congestion at the terminals for external vehicles, the maximum number of TSBs sent to T1 has to be adapted. This is reduced by 3.55 for every case, which rounded would reduce each setting by an average of four vehicles. This way there will be less congestion at T1 and a more balanced allocation to T2 and T3.

4.5.3. Design 4: Extra switches at berth

Design 4, as described in Section 3.7, introduces modifications to the berth layout compared to Design 1. It incorporates short tracks between the fast track and the berth track of the terminal, serving as shortcuts for TSBs to bypass congestion at the berth.

This section will discuss the adjustments made for Design 4, focusing on the assignment of vehicles to the berth track and fast track, as well as the operation of the shortcut switches at both tracks.

Pre-berth switch assignment
The operation for external vehicles and vehicles heading to the yard will remain unchanged from the main design, directing them to the fast track. However, for vehicles destined for the terminal berth, the following rules will determine which track they take, either directly to the vessel's berth via the berth track or via the fast track followed by the shortcut:

- TSBs headed to berth 1 will always be directed directly to the berth track since it is the first berth and is no congestion to skip.
- For destinations beyond berth 1, the algorithm will check if any of the preceding berth spaces have more than four TSB vehicles. If any berth space before the corresponding one has more than four vehicles, it indicates congestion, and the vehicle will be directed to the fast track instead. This allows it to take the shortcut and bypass the congestion.

Berth shortcut switches operation
If a vehicle is assigned to take the shortcut, when it reaches the corresponding berth shortcut switch on the fast track, it will proceed in that direction. As the fast track switch opens, the algorithm checks if there are any vehicles on the berth track between the previous berth space and the switch. If there are no vehicles, the switch at the berth will also open, allowing vehicles to pass through the shortcut directly to the berth.

Upon entering the shortcut, before reaching the switch to the berth track, the vehicle will again check for vehicles on the berth track. The following rules apply:

- If the switch is in the berth position or if there are multiple vehicles on the berth track, the shortcut vehicles will wait until these vehicles pass. Once clear, the switch is adjusted to the shortcut position, allowing vehicles to proceed.
- If the switch is in the shortcut position and there are no vehicles on the berth track, but QC4 of the destination berth is occupied, the shortcut vehicles will wait until QC4 is freed. After QC4 is available, the algorithm will check again. If there are TSBs on the berth track, they will be allowed to pass first, as they are either loaded with an import container or destined for a further berth. This helps decrease congestion and increase operational efficiency.
- If the switch is in the shortcut position, there are no vehicles on the berth track, and QC4 is free, then the vehicles at tjhe shortcut will directly pass to the berth.

4.5.4. Design 5: Standard system without intra-terminal transport
Design 5, as already discussed in Section 3.8, introduces several changes to the standard system, particularly in the utilization of Automated Guided Vehicles (AGVs) and the handling of intra-terminal transport. The key adaptations and assumptions for this design include:

- AGV Implementation: AGVs are deployed only in Terminal 1 (T1), while Terminals 2 (T2) and 3 (T3) continue to rely on TSBs for transport operations.
- Handling of Container Types: TSBs are responsible for managing import Intra-Terminal Transport (ITT) containers and dry port containers, while AGVs handle all transport from the terminal yard to the vessels' berth, including rail and transshipment containers, as well as export ITT containers.
- QC Capacity: The Quay Cranes (QCs) are equipped to handle both AGV and TSB containers, and have the capacity of selecting containers based on their intended mode of transport.
- Availability of AGVs: AGVs are always available at the berth when no TSBs are available, ensuring continuous operation.
- Operation Time: After loading or unloading an AGV, there is a 15-second interval for the next AGV to be positioned and for the next QC operation to commence.
- TSB Container Assignment: Each TSB container is assigned both an origin QC and a destination QC, in contrast to TSBs that do not have defined QC assignments.
- AGV Operation Mode: AGVs operate on a single-cycle basis, performing only one operation at a time, unlike TSBs, which can perform sequential unloading and loading operations.
- System Halt: If there are no containers available for TSB handling, the system will pause, and TSBs will wait upstream of Terminal 2.

These adaptations are integrated into the model to optimize the operational efficiency of the terminal while streamlining the transport process using AGVs and TSBs. Next, we will delve into the specifics of the AGV loading assignment algorithm.

Algorithm AGV loading
The AGV loading algorithm operates as follows:

1. Initialization: Each Quay Crane (QC) maintains a list of import containers destined to be loaded onto Automated Guided Vehicles (AGVs) and export containers intended for vessel loading.

2. Vessel Berth Check: Upon the vessel's arrival at the berth, the algorithm checks if there are any TSBs assigned to the vessel at the berth. If no TSBs are assigned, the algorithm proceeds to the next step.
3. Container Movement: For each QC, the algorithm checks if there are containers available in the list of import containers destined for AGVs. If containers are available, the QC initiates the movement of containers to AGVs, or AGV container to vessel. After each container move, a 15-second interval is observed before positioning the next AGV.
4. TSB Arrival at QC4: When a TSB arrives at QC4, it is assigned to the QCs as per the standard model. If the assigned QC is currently occupied with an AGV container, the TSB waits until the QC operation is completed.
5. TSB Loading Operation: Once the assigned QC becomes available, the TSB loading operation commences. Upon completion of the TSB loading operation and departure of the TSB vehicle, the algorithm reevaluates the availability of TSBs.
6. Continued Operation: The algorithm continues to alternate between processing AGV containers and TSB loading operations until all containers have been processed.
7. Vessel Departure: Once all TSB and AGV containers have been processed, the vessel is ready to depart from the berth, following the completion of loading operations as per the standard procedure.

This algorithm ensures the efficient handling of container movements, balancing between TSB and AGV operations to optimize the loading and unloading processes at the terminal berth.

Adaptation max number of TSBs sent to T1
In Design 5, where there is no intra-terminal transport and all containers are destined for the dry port (DP) except for barge and ITT containers, an adjustment needs to be made to the maximum number of TSBs sent to Terminal 1 (T1). This adjustment is necessary due to the difference in average time per container between a round tour of the yard with loading and unloading (6.5 minutes) and a tour to the DP (23.6 minutes) in perfect conditions. This leads to the average time per container being 1.94 times higher than for the base setting. Additionally, there is a lower share of T1 volumes being handled by TSBs compared to the overall volume. To adapt to this scenario, the maximum number of TSB vehicles sent to T1 is multiplied by a factor of 1.94. This adjustment ensures that T1 receives an appropriate number of TSBs relative to the total amount of vehicles in the system.

4.6. Validation and Verification

The validation and verification of the simulation model involve several steps to ensure its accuracy and reliability.

Validation:

1. Comparison with Real-world Data: The model outputs are compared to real-world data to assess their consistency and accuracy. This involves checking if the simulation results align with actual operational outcomes observed in the terminal. This is done in the Results chapter.
2. Field Expert Opinion: Input and feedback from domain experts, included in the Discussion section 6, provide valuable insights into the simulation's realism and effectiveness in representing real-world processes and dynamics.
3. Sensitivity Analysis: Various scenarios with fluctuations in input data are tested to gauge the sensitivity of the model and assess its robustness. This helps identify critical parameters and their impact on the simulation outcomes, detailed in the Results chapter.

Verification:

1. Unit Testing: The simulation undergoes rigorous unit testing to validate its individual components and functionalities. This includes visually checking and tracking container and vehicle movements within the model and comparing them with the expected behavior and final statistics.
2. Scenario Testing: Different design scenarios, represented by Designs 1 to 5, are tested to evaluate their impact on the system's performance and the behavior of agents. This allows for assessing how changes in the terminal's design and operation affect overall efficiency and effectiveness, in addition to potentially identify any unexpected model behavior .
3. User Feedback: Feedback from end-users, particularly the TSB department of Max Bögl, is gathered to validate the technical attributes and functionality of the TSB system within the simulation. This feedback helps ensure that the simulation accurately reflects the operational realities of the transport system and challenges faced by terminal operators.

By employing a combination of these validation and verification methods, the simulation model aims to achieve a high level of accuracy, reliability, and relevance to real-world terminal operations.

4.7. Conclusion

In this chapter, we constructed a comprehensive simulation model utilizing Siemens Tecnomatix Plant Simulation software to evaluate the performance of the TSB system within a port logistics framework. Through meticulous design and implementation, we captured in the model the complex dynamics of container handling, vessel operations, and inter-terminal transport, considering various design modifications and operational rules. Key components included the simulation of vessels, quay cranes, terminal yard, dry port, and external terminals, each governed by specific operational scheduling and assignment rules, and parameters.

Looking ahead, the five simulation models outlined in this chapter will be subjected to rigorous testing and analysis in Chapter 6, where input data, scenario explanations, and results will be presented and evaluated.

5
Results & Scenarios

In this chapter the five designs from Chapter 3 and the according simulation explained in 4 are tested and analyzed thought different scenarios and sensitivity analyses.

5.1. Scenarios

Each design undergoes testing across various scenarios, categorized into two groups. The first set comprises four scenarios (refer to Figure 5.1) involving adjustments to the demand volumes of T1: the base scenario, +5% demand, +10% demand, and +20% demand. The second set includes four scenarios (refer to Figure 5.2) focusing on changes in modal shares: the base scenario, +10% road/-10% rail, +5% rail/-5% road, and +5% ITT/-5% in-terminal transshipment. Each scenario is evaluated across multiple different operational configurations of TSBs (see Table 5.3), depending on the specific scenario, to analyze the impact on the required number of vehicles and the resulting outcomes. The scenarios with varied demand volumes are designed to assess the system's responsiveness to increases in demand, identify potential bottlenecks, and determine the system's capacity. Furthermore, these scenarios aim to ascertain whether increasing the number of vehicles can effectively manage heightened demand or if a saturation point exists beyond which further improvement is unattainable. The modal split scenarios are intended to explore how different distributions of demand among transportation modes may affect the system's performance. All scenarios will be rigorously tested in this chapter.

	Scenario 1		Scenario 2 (+5%)		Scenario 3 (+10%)		Scenario 4 (+20%)	
T1	133,250	31%	139,913	32%	146,575	33%	159,900.00	35%
T2	149,521	35%	149,521	34%	149,521	34%	149,521	33%
T3	149,521	35%	149,521	34%	149,521	34%	149,521	33%
total	432,292		438,954		445,617		458,942	

Figure 5.1: Demand increase scenarios. Unit: containers.

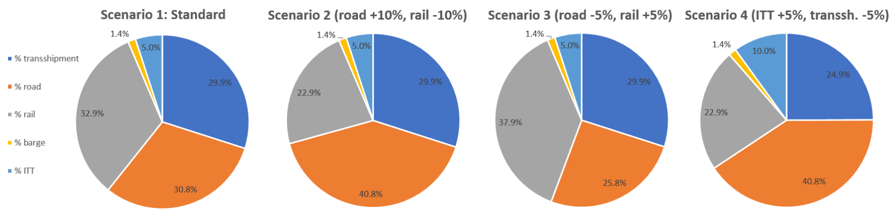

Figure 5.2: Modal split scenarios.

Scenario	Design 1: Base design	Design 2: Shortcut	Design 3: Double track	Design 4: Extra switches	Design 5: No intra-terminal transport
Standard	80, 85, **90**, 95	80, 85, **90**, 95	90, **95**, 100, 105, 110	85, **90**, 95, 100	65, **70**, 75, 80
+5% demand	85, 90, 95, 100	85, 90, 95, 100	95, 100, 105, 110, 115	90, 95, 100	70, 75, 80
+10% demand	90, 95, 100, 105, 110	90, 95, 100, 105	100, 105, 110, 115	95, 100, 105	70, 75, 80
+20% demand	95, 100, 105, 110	95, 100, 105, 110	110, 115, 120	100, 105, 110	70, 75, 80
+5%rail / -5%road	80, 85, 90, 95	80, 85, 90, 95	90, 95, 100, 105	85, 90, 95	65, 70, 75
+5% ITT / -5% transsh.	85, 90, 95	85, 90, 95	95, 100, 105, 110	90, 95, 100	-
+10%road / -10%rail	90, 95, 100	90, 95, 100	95, 100, 105, 110	90, 95, 100	70, 75, 80

Figure 5.3: Number of TSB vehicles tested for each design and scenario. Each design's main setting is highlighted in red.

5.2. Design 1: Standard design

This first scenarios analysis corresponds to Design 1 (3.4).

5.2.1. Main setting

The main setting analysis is done for the standard demand and with 90 TSB Cargo trains to fulfill the whole container movement of the current demand

Terminal 1

- Average berth time: 16.3h
- Median berth time: 14.5h
- Average containers/hr: 101.9
- Termination time: day 29.97

These vessel berth times improve the benchmark of 0.79 days of median berth time (18.96hrs) (source: UNCTAD, 2019) and is able to be completed in the scheduled time, before the maximum allowed termination time, and is therefore considered successful.

Figure 5.4 illustrates the real time volumes to be handled for terminal 1, encompassing import containers requiring unloading from vessels or transportation from various storage locations to the berth for loading onto vessels. The blue line in the figure represents the total daily demand based on vessel arrival schedules, indicating how container to be handled peaks align with vessel arrivals, and their corresponding demand. Every time volumes peak up signified the arrival of a vessel, therefore the objective is to efficiently manage these arriving vessels, decreasing the volume of containers to be handled in the minimum time possible, in order to minimize berth times and minimize vessel turnaround. As depicted in the figure, the peaks decrease rapidly, highlighting the importance of timely handling. Failure to address these peaks promptly results in volumes build up, leading to congestion at the berth and subsequent waiting times for arriving vessels. Additionally, the simultaneous management of import and export volumes maintains similar volume levels to minimize imbalances and empty trips, thereby enhancing operational efficiency.

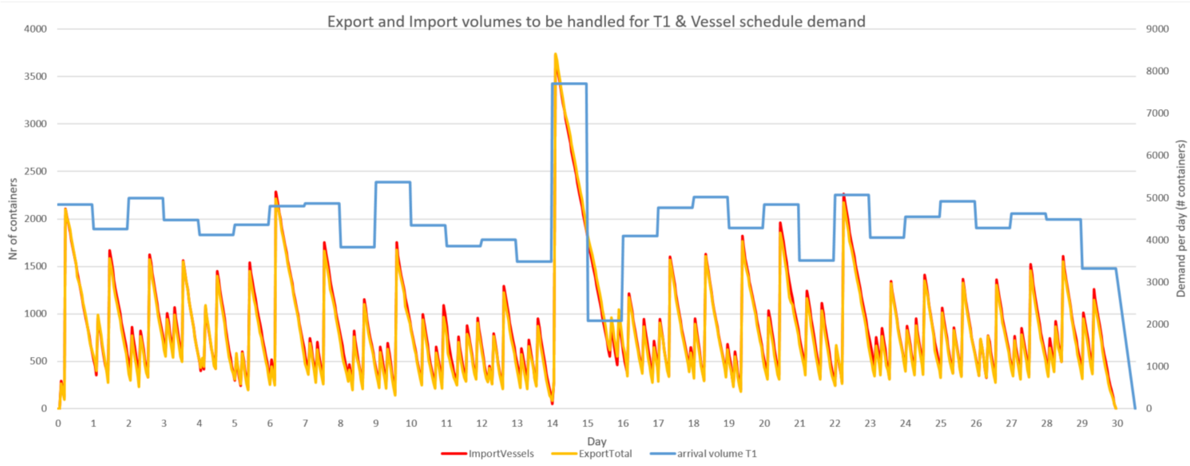

Figure 5.4: Import and export volumes to be handled for T1. As the container is handled the volume decreases, therefore low levels are preferred. The blue line show the vessels demand volume per day. Unit: number of containers to be handled.

Figure 5.5 depicts these volumes with the export containers divided by their current storage locations: dry port, transshipment and rail. Despite these different categories having varying shares, they are handled simultaneously, as depicted by the practically parallel lines. The analysis reveals a consistent trend where dry port volumes remain relatively lower compared to rail export and transshipment containers. This can be attributed to several factors. Firstly, the dry port transport mode typically commands the smallest share among the three, influencing its lower volume levels. Additionally, it serves as the initial transport mode activated upon vessel arrival, with TSB vehicles dispatched from the dry port to the terminal, further influencing its lower volumes. Subsequently, rail export containers typically follow in volume, with transshipment containers exhibiting the highest demand volumes, thus corresponding to the sequential order of demand shares.

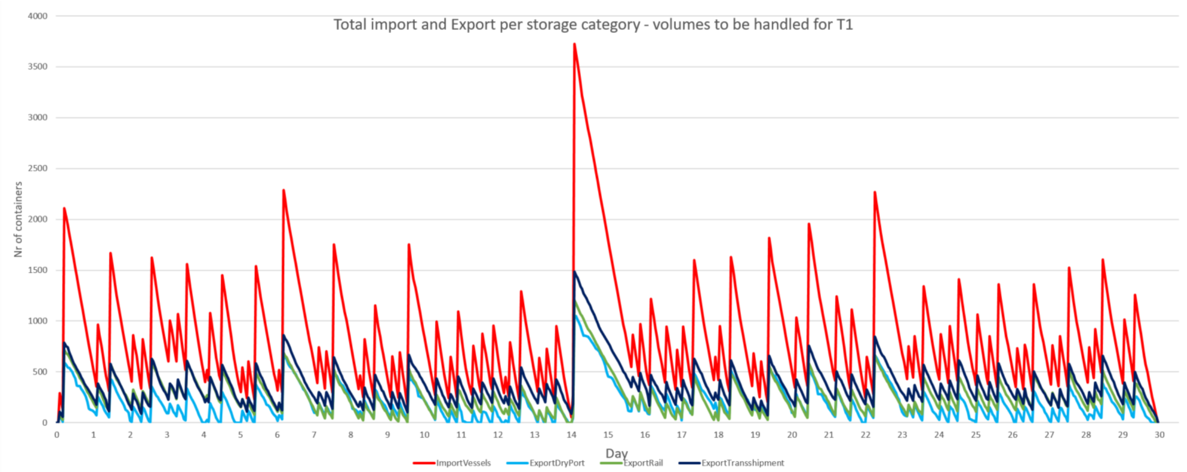

Figure 5.5: Import and export volumes to be handled for T1, with the export being divided in its three different storage locations: dry port, transshipment and rail. As the container is handled the volume decreases, therefore low levels are preferred.

Figure 5.6 displays the berth times of 80 vessels represented by columns, spaced over their departure from the berth. The green line depicts the average berth time per hour of vessels berthed at that moment, indicating an increase in average berth time as the column size increases and columns become more spaced out. The absence of a zero average berth time indicates continuous vessel presence at the berth. When the linear increase of the green line is interrupted, it signifies either a vessel departure or arrival, resulting in a decrease in average berth time.

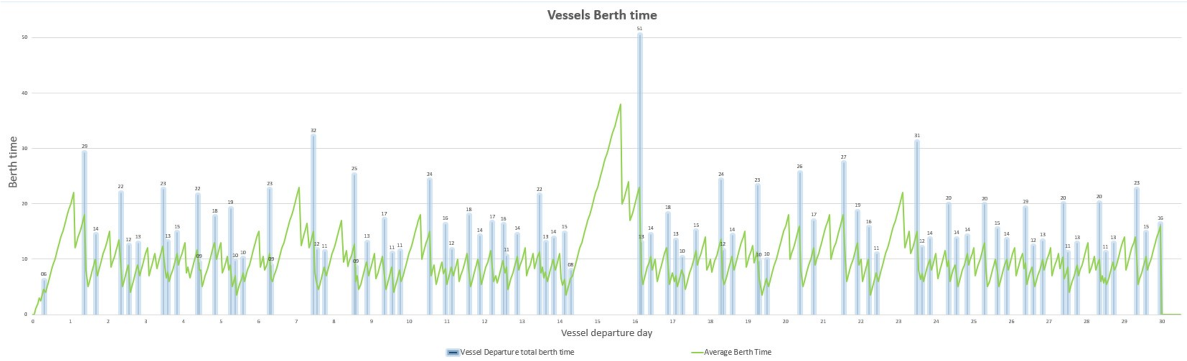

Figure 5.6: Vessels berth time by port departure depicted by the blue columns and the hourly average total berth time by the green line.

Additionally, Table 5.7 illustrates how vessels with higher berth times correspond to those with higher total throughput (import + export). For instance, vessel 41, with the highest throughput volume of 7096 containers, also has the highest berth time of 50.57 hours. In practice, terminals would employ a greater number of quay cranes to minimize these peaks and enhance the efficiency of handling large vessels. Although this simulation used a standard number of four quay cranes, terminals typically have movable quay cranes, enabling optimization of berth space utilization and reducing berth times.

VesselNr	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
berth time (h)	6.2	29.3	14.4	22.0	12.5	12.9	22.6	13.1	14.8	21.6	9.4	17.7	19.2	9.6	10.2	22.6	8.9	32.2	11.7	11.3
total volume	690	4155	1400	2857	1086	1201	2710	998	1151	2323	422	1517	2186	711	889	2766	624	4181	880	917

VesselNr	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
berth time (h)	25.2	8.6	13.1	17.1	11.0	11.5	24.3	16.3	11.8	18.0	14.2	16.7	16.3	10.6	14.5	21.6	13.0	13.9	14.8	7.9
total volume	3072	480	1340	2007	983	1068	3322	1605	963	1784	1110	1306	1436	488	1229	2286	843	1109	1534	607

VesselNr	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60
berth time (h)	50.6	13.0	14.5	18.3	13.4	10.3	15.1	24.3	11.6	14.3	23.3	9.7	9.9	25.7	16.9	27.4	18.7	15.7	10.9	31.2
total volume	7096	833	1252	1865	1243	984	1428	2687	655	1338	2813	866	880	3399	1531	3306	1827	1689	987	4085

VesselNr	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80
berth time (h)	12.1	13.7	20.0	13.7	14.2	19.9	15.5	13.5	19.3	12.3	13.3	20.0	11.2	12.9	20.2	11.2	12.9	22.7	14.8	16.4
total volume	800	1031	2228	1061	1296	2193	1582	1134	2203	941	1082	2264	964	1178	2487	930	1183	2371	1439	1883

Figure 5.7: Berth time and total volume per vessel.

External terminals

Figure 5.8 illustrates the total volumes to be managed for T2, T3, and the barge terminal. Noticeably, the barge volume remains minimal, and terminals 2 and 3 exhibit controlled volumes, with rapid declines in peaks and no significant buildup of volumes. Figure 5.9 presents two separate graphs depicting import and export volumes for T2 and T3. This comparison offers a clearer insight into how import-export volumes are consistently balanced for each terminal, with import volumes typically slightly higher, reflecting an import share of 50.6%. Additionally, the graphs reveals the mirrored pattern of the vessels schedules, with days 1-15 of T2 corresponding to days 15-30, and vice versa, as previously explained in the input data section (see Section 4.3).

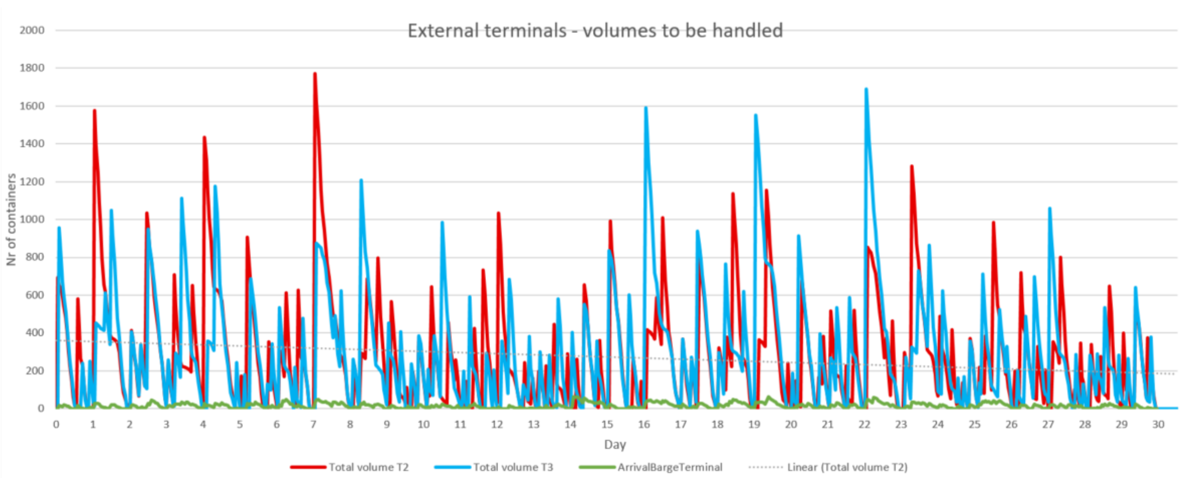

Figure 5.8: External terminals (T2, T3 and Barge terminal) volumes to be handled per hour.

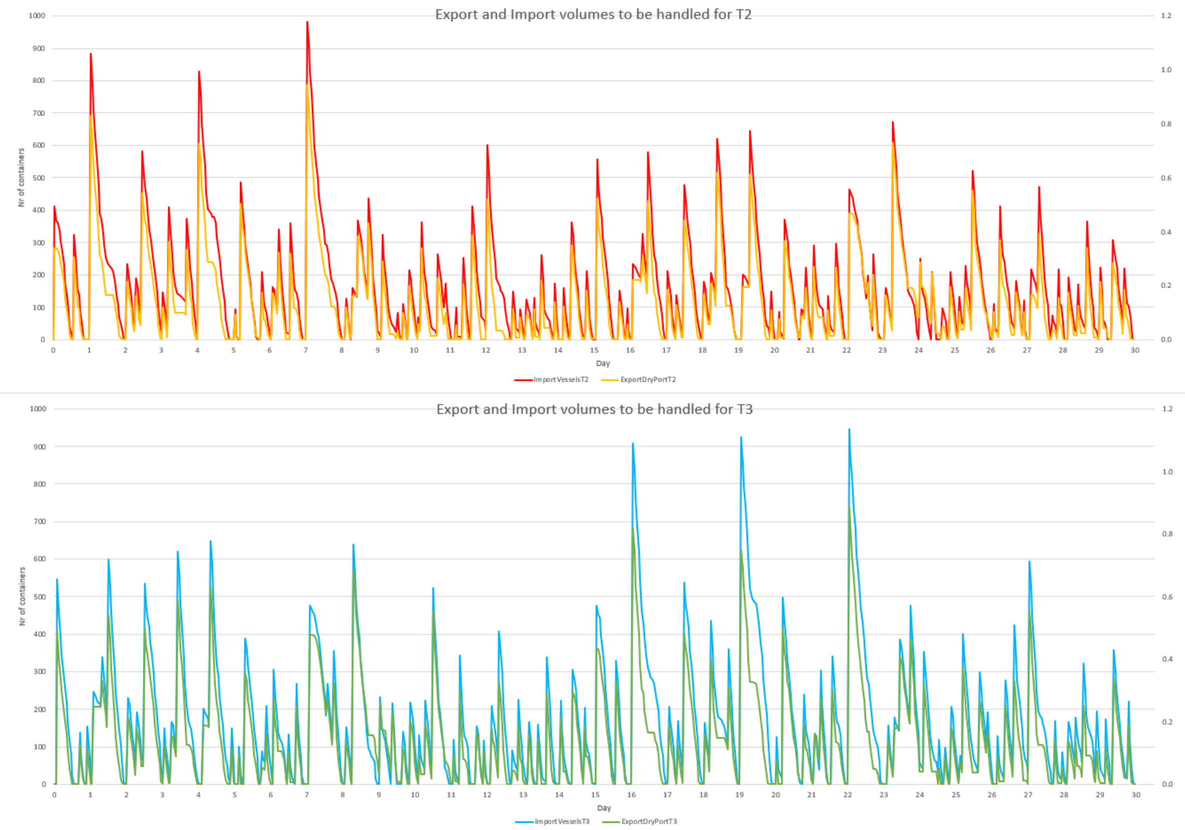

Figure 5.9: Export and import volumes T2 (top) vs T3 (bottom).

All terminals

After individually analyzing each terminal, the collective analysis of all three terminals is presented, with Figure 5.10 showcasing the hourly data of the volumes to be managed, and Figure 5.11 providing the same data averaged per day for clarity. Notably, volumes for T1 consistently exceed those of T2 and T3 by an average factor of 5.92. Several factors contribute to this discrepancy.

Firstly, the method of dispatching containers from the dry port to T2 and T3 differs from that to the main terminal. For the main terminal, container dispatch relies on the current number of vehicles at the terminal and ongoing vehicle assignments with the same destination. In contrast, dispatch to external terminals is contingent upon the number of vehicles assigned to T1 and the availability of containers at T2 and T3 (see Section 4.4.5). Consequently, the fluctuation in the number of TSBs sent to T2 and T3 leads to more pronounced peaks and valleys, resulting in a faster decline in demand volumes and subsequently lower average volumes.

Moreover, since T2 and T3 are modeled as black boxes, the intra-terminal container movements (rail, transshipment, and yard-berth movement for ITT and barge containers) are not explicitly modeled, accounting for 65.55% of the volume. This absence contributes to the notably lower volume apparent in T2 and T3. Consequently, the total modeled volume for T1 is 240% of T2 and T3.

Another contributing factor is the buffer time added for TSB vehicles at the external terminals (14 minutes and 12 seconds) operating under optimal conditions. In contrast, at the main terminal, interaction with QCs and yard RMGs introduce additional delays due to congestion.

Furthermore, the vessel schedule for T1 was designed with more volume fluctuations, as depicted in Figure 4.5, resulting in higher average volumes.

Overall, the simulation aims to manage volumes consistently across all three terminals, avoiding volume buildup in one terminal while others are underutilized. This is demonstrated by the linear trend line in the graphs, depicting a negative slope (-13.5) indicative of controlled and stable container volumes across all terminals.

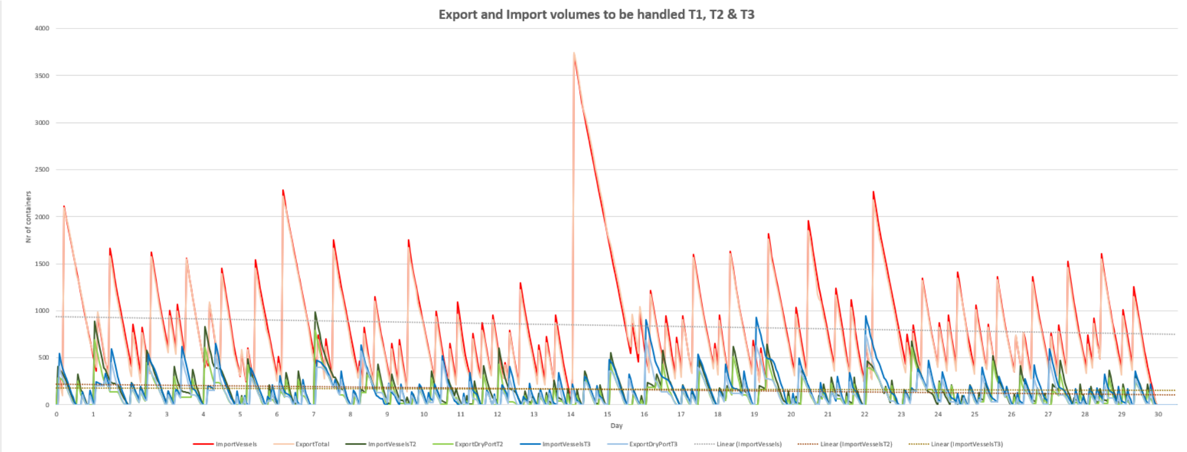

Figure 5.10: Import and export hourly volumes T1, T2 and T3. The linear trend of the import volumes represented by the dotted lines.

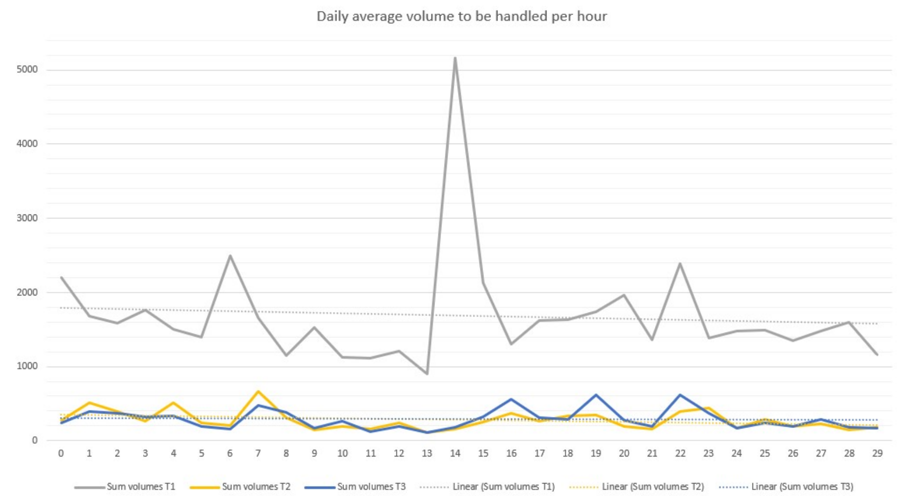

Figure 5.11: Daily average volume per hour per terminal and their trend-lines in dotted lines.

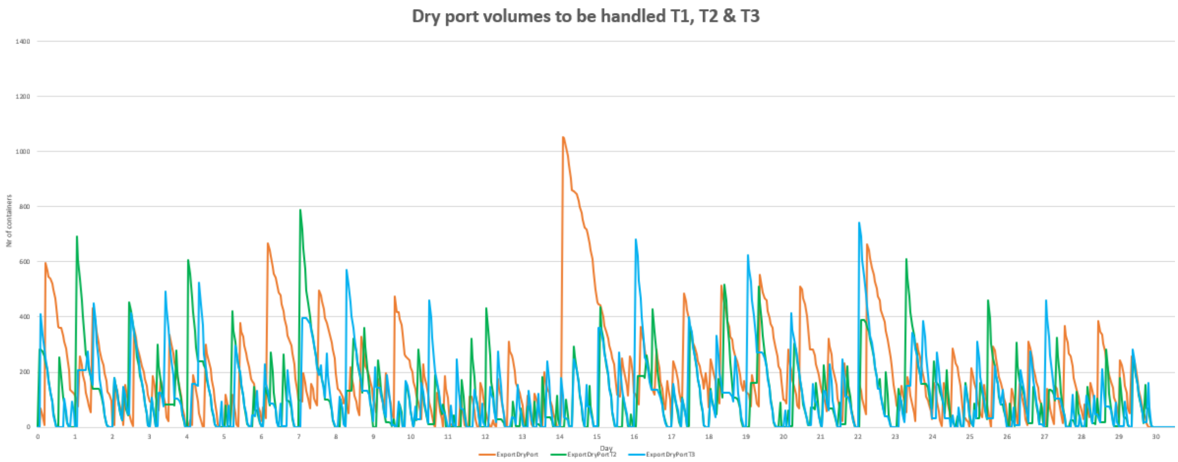

Figure 5.12: Dry port storage volumes of T1, T2 and T3.

TSB vehicles

With the current utilization of 90 TSB vehicles, each vehicle covers a total distance of 4468.9 km. On average, a single trip around the entire system, starting from a terminal, passing through the dry port, and returning to the terminal (excluding intra-terminal and fast-tracks), spans approximately 52.3 km. This equates to roughly 28.5 trips around the system per TSB vehicle per day. The minimum trips required to the dry port, serving import containers for T1, T2, and T3, amount to 25 trips per day. The remaining distance accounts for empty trips, movement between terminals for in-terminal transportation (ITT), and intra-terminal transportation at T1, in addition to other operational inefficiencies. Notably, there are considerable distances covered by ITT containers, which need to traverse the dry port to reach other terminals. This issue is expected to be addressed in Design 2, as discussed later in section 5.3. Additionally, Figure 5.13 presents the total simulation moves of the system, totaling 237,929 moves, resulting in an average of 16.9 km per container move.

Figure 5.14 illustrates the time distribution of TSB usage, revealing that 50% of the time is spent in motion, while 21% is allocated to buffer time at external terminals, and 29% is dedicated to waiting or being stationary. Although the waiting time may seem significant, a considerable portion of it is attributed to (un)loading time by cranes, which is unavoidable. Additional waiting time is incurred due to congestion, primarily at the berth, and queuing at the yard or dry port while awaiting crane assignments. Furthermore, a small portion of waiting time is caused by switches, either waiting for them to move into position upon vehicle arrival or waiting while they are open for vehicles in other tracks. This latter issue could be mitigated by initiating switch movements prior to vehicle arrival, although in this simulation, switches are only activated upon vehicle arrival.

Moreover, the table indicates that 14% of the total time is spent by vehicles being empty, mainly due to container imbalances. However, this could be minimized through more efficient container assignment, the implementation of a double-direction track, or the incorporation of a shortcut around the port, as proposed in subsequent designs.

Nr vehicles	90
Average covered Distance per TSB	44680.9
% moving time	50%
% waiting/stopped time	29%
% time at external terminals	21%
% time empty	14%
total Simulation moves	237929

Figure 5.13: TSB statistics for 90 vehicles. Distance in km.

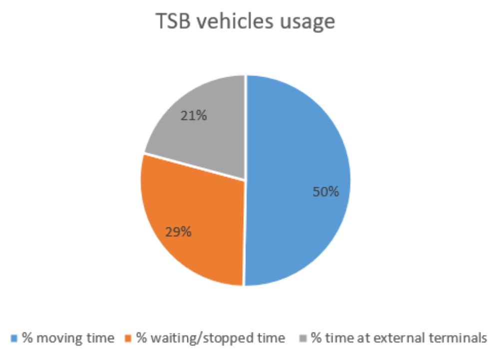

Figure 5.14: TSB vehicles usage %. The waiting/stopped time represents the time the vehicle is stopped while (un)loading by a crane, or stopped in congestion or waiting for a switch move. External terminals time refers to the time the TSB vehicles spend at the buffers at T2, T3 and barge terminal.

Cranes

Concerning the productivity of quay cranes, Figure 5.15 illustrates the performance of the sixteen quay cranes across the four berth spaces. With an average net working time of 57% and 25.45 handling moves per hour (based on the occupied time per berth), these figures align with industry standards, which typically range between 25-30 moves per hour (Navis, 2015). While these metrics fall short of technical productivity, they are consistent with industry norms, reflecting inefficiency losses stemming from scheduling and queuing, which impede achieving maximum productivity. It can also be seen how the productivity for berth A QCs (first berth, 26.2 moves/hr) is higher than for the other three. This is because the vehicles with berth 1 destination avoid the congestion of other berth spaces, and therefore containers are loaded into the vessel faster. In section 5.5 , we delve into the analysis of the design incorporating extra switches between the fast track and the berth track. The expectation is that this adjustment will alleviate congestion issues by allowing vehicles to bypass queues formed at preceding berths.

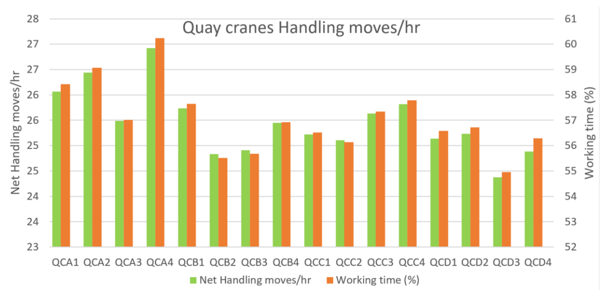

Figure 5.15: Quay cranes net productivity and net handling moves per hour.

Regarding the productivity of yard and dry port RMGs, Figures 5.16 and 5.17 present these metrics. Comparing these figures to industry benchmarks is challenging due to significant variations influenced by factors such as the size of storage blocks, number of cranes, container rotation (dwell times), and other operational variables.

For dry port cranes, the import cranes exhibit more imbalance as there is no specified destination for containers, and the assignment rule tends to direct empty cranes to the furthest location. Conversely, the export cranes demonstrate better balance due to the specified origin of containers. On average, these cranes handle 8,314 containers at a rate of 11.4 per hour for export and 11.8 for import. Based on the gate opening times for dropping and picking up containers by truck at the HHLA CTA terminal, which operates a total of 128.5 hours per week (source: HHLA, 2023), the average available time per truck for import containers is 3.9 minutes, while for export containers it is 4 minutes. Considering an appointment system implemented to balance truck arrivals throughout the operating period (see Section

2.1.3 for further details), and factoring in the time required for RMGs to handle containers (90 seconds per move), it is evident that this setup is entirely feasible for truck operations.

Similarly, yard cranes also display slight imbalance, with the furthest crane typically handling slightly more moves. This tendency arises because when a TSB has to drop a container and not pick up another one, are often assigned to the furthest crane. Rail yard cranes achieve an average productivity of 12.2 containers per hour with a working time of 24%, while transshipment cranes achieve 13.4 containers per hour with a 26% working time, reflecting the higher transshipment volumes compared to rail operations. During the remaining 76% of the time when the rail RMGs are not occupied with TSB containers, they can be utilized for rail lift-AGVs. As previously explained, lift-AGVs work with racks, allowing the cranes to operate independently from the AGVs. This means that the cranes can load or unload containers to and from the rack whenever these are available and not being requested for a move by a TSB vehicle, without having to wait for an AGV or an AGV wait for the crane. This arrangement further demonstrates the feasibility of the system.

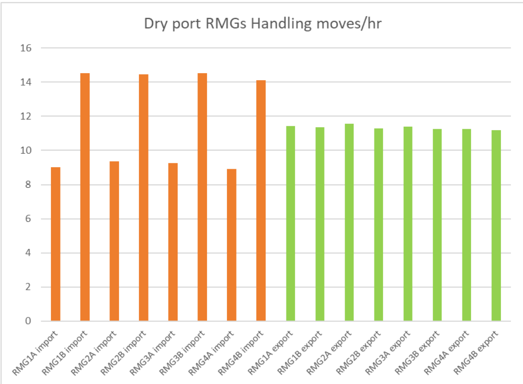

Figure 5.16: Dry port RMG import and export cranes gross handling move per hour.

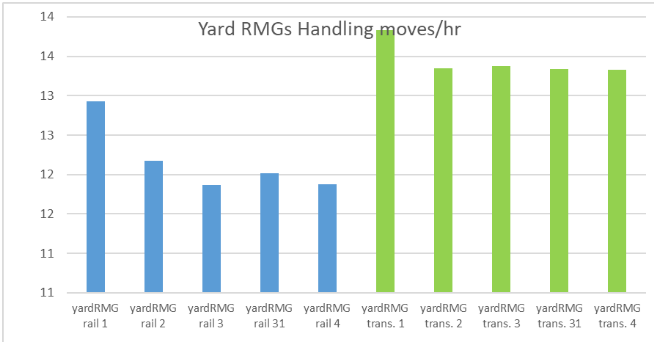

Figure 5.17: Yard RMG rail and transshipment cranes gross handling moves per hour

5.2.2. Demand increase scenarios

For these scenarios different number of operating TSBs are set:

- Standard: 85, 90 and 95
- +5% demand: 85, 90, 95 and 100
- +10% demand: 85, 90, 95, 100 and 105
- +20% demand: 95, 100, 105 and 110

Vessels

Figures 5.18 and 5.19 depict the berth time for the various scenarios. It is evident that as the number of TSBs increases in each scenario, the berth time decreases. However, there is an observed inverse exponential trend in berth time as the number of TSBs rises. Moving from the standard scenario to the +5% scenario, roughly 5 additional TSB vehicles are required to achieve similar results. However, the increase in TSB vehicles needed becomes more pronounced as we progress from the +5% to the +10% scenario and further to the +20% scenario. This difference in the number of vehicles becomes more significant as the scenarios approach their minimum possible berth time. There may be a threshold where an excessively high number of vehicles could become counterproductive, leading to increased congestion rather than improvement. For instance, testing the +20% scenario with 120 TSBs results in a median berth time increase to 19.5, despite a slight decrease in the average berth time.

In Figure 5.20, we observe a decrease in the productivity rate of containers per hour in higher volume scenarios. This reduction is attributed to the longer unloading times for higher volume vessels, contributing to increased congestion at the berth and a delay in dispatching vessels, thereby prolonging the time taken to focus on operations of the subsequent vessels, even tho already initiated, as it was demonstrated that the efficiency of vessel operations increases with fewer vessels at berth.

This bottleneck is not solely attributed to infrastructure but also to crane resources. In the event of increased volumes, the number of cranes, especially quay cranes, should be adjusted accordingly. The current configuration of four quay cranes may prove inadequate for handling vessels with high volumes.

Furthermore, Table 5.21 presents the simulation end times, indicating when the vessel schedule is completed for all terminals. The scheduled arrival of the last vessel at T1 on day 29.3, with two new vessels arriving for the new month's schedule on day 30, at hours 0 and 4. Thus, if a vessel has not departed the port by more than half a day, it indicates a potential delay in the subsequent month's schedule, exacerbating any existing backlog issues, and therefore highlighted in red on the Table.

Volume T1	85	90	95	100	105	110
standard	21.6	14.5	12.7			
+5%	24.7	17.1	14.6	13		
+10%	30.5	24.94	19.8	17.1	16.9	
+20%			30.3	25	21.2	19.3

Figure 5.18: Median vessels berth times table per scenario and number of TSB vehicles used. The color range ranks the scenarios outputs from best (green) to worse performer (red). Unit: Hours.

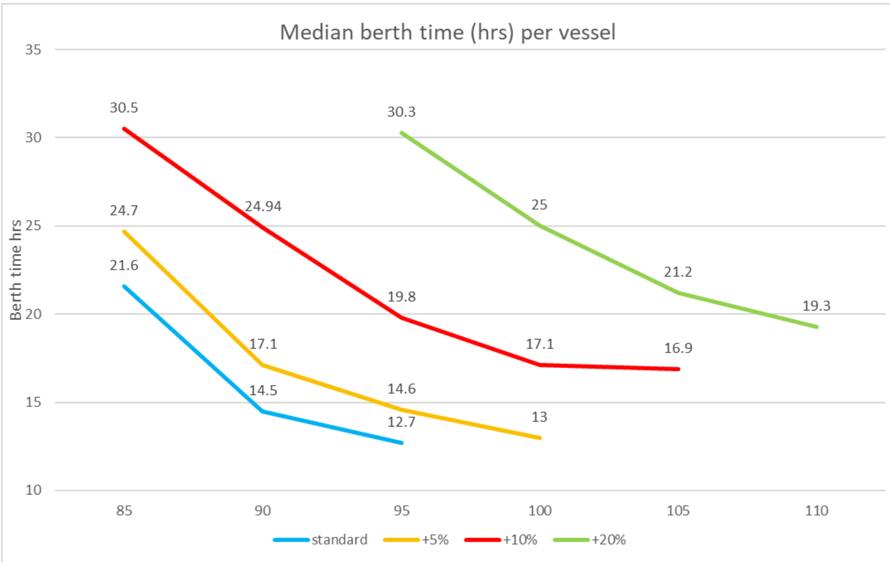

Figure 5.19: Median vessels berth times graph per scenario and number of TSB vehicles used. Unit: Hours.

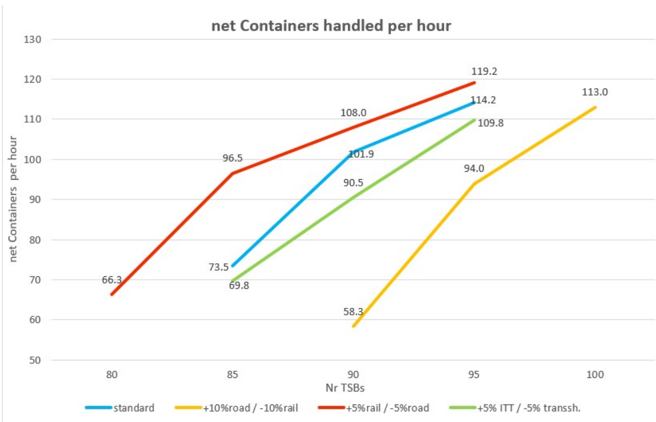

Figure 5.20: Net containers handled per hour per scenario and number of TSB vehicles used. Net: Total containers/total berth time hours

Volume T1	85	90	95	100	105	110
standard	30.6	30.0	29.9			
+5%	31.1	30.3	30.0	30.0		
+10%	32.0	30.8	30.3	30.0	30.0	
+20%			31.4	30.8	30.4	30.2

Figure 5.21: Schedule end time per scenario. Red cells represents scenarios in which the end time surpassed the maximum expected time (30.6), in which the vessels schedule starts to have a delay, meaning the system setup is not feasible to handle the scenario demand. Unit: Hours.

Volumes to be handled

Figure 5.22 illustrates the daily average total containers to be handled for all terminals throughout the month. It identifies the scenarios with the lowest performance, corresponding to the lowest number of TSBs tested for each scenario, as discussed previously. Conversely, among the better-performing scenarios, several are closely aligned, warranting further examination in the subsequent paragraph. The graph also reveals a pattern following the vessel scheduled volumes across all scenarios. However, in scenarios with lower performance, the demand doesn't decrease sufficiently before rising again, leading to a continuous buildup and delays in the long run, rendering these scenarios unfeasible. Conversely, for scenarios at the bottom of the graph, volumes are maintained stable and controlled, exhibiting a non-positive linear trend.

Figures 5.23, 5.24, 5.25, and 5.26 display the same graph segmented by demand scenarios for clearer visualization. As observed previously with berth times, a significant difference in performance is evident between the lowest and second-lowest TSB settings. However, as performance approaches optimal, increasing the number of TSBs yields diminishing improvements. Nevertheless, in 5.25 and 5.26, a gradual buildup of volumes is apparent at the second-lowest TSB settings (90 and 100, respectively).

This buildup is also depicted in Figure 5.27, which presents the slope index, representing the stability of the volumes. A positive slope indicates volume growth over time, which over a month may not be problematic if not excessively high, but over an extended period, it could lead to significant delays and system overload, resulting in failure to handle demand efficiently and on time. While a slope of ten units may still be manageable, a steeper slope would render the system unfeasible. As illustrated, except for the aforementioned scenario, all others exhibit a negative slope, indicating successful performance. These findings align with the conclusions drawn from the end times depicted in Figure 5.21.

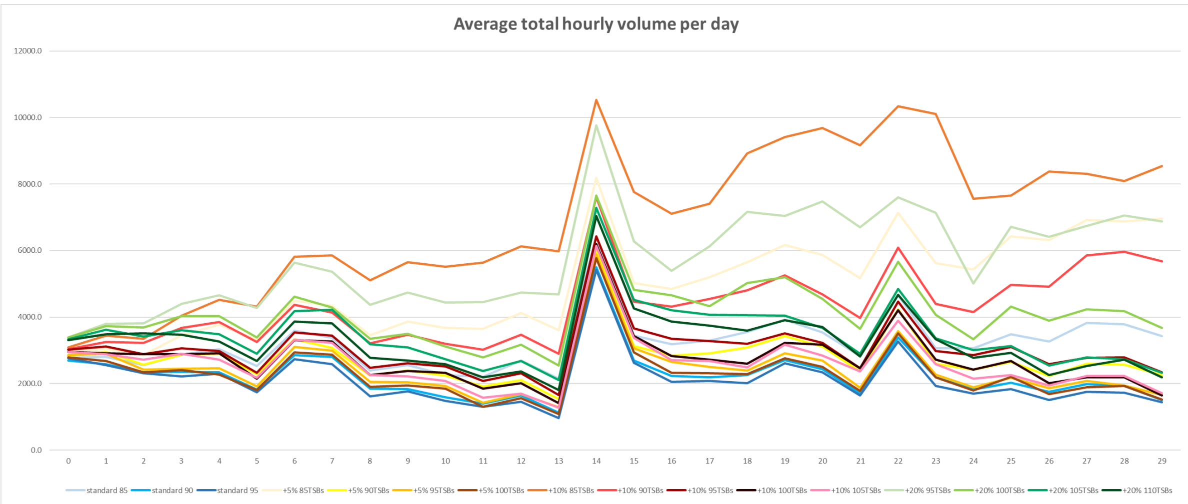

Figure 5.22: Daily average hourly total volume to be handled for all different scenarios.

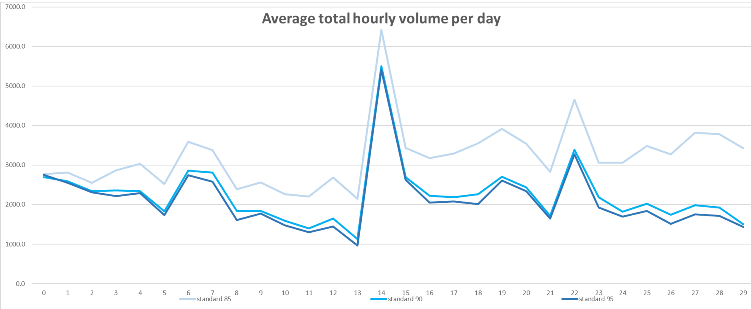

Figure 5.23: Daily average hourly total volume to be handled for scenario 1, standard demand of T1.

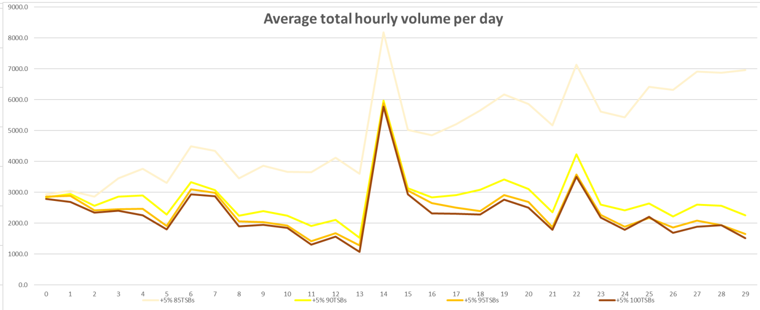

Figure 5.24: Daily average hourly total volume to be handled for scenario 2, +5% demand of T1.

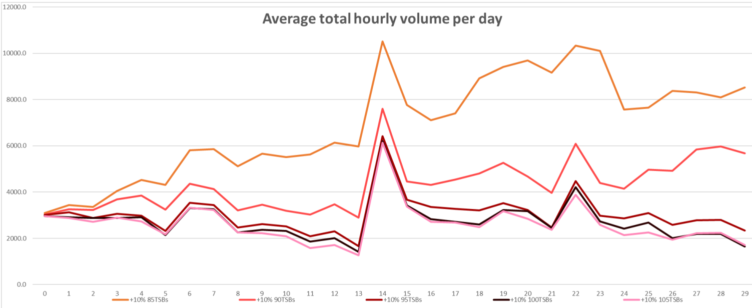

Figure 5.25: Daily average hourly total volume to be handled for scenario 3, +10% demand of T1.

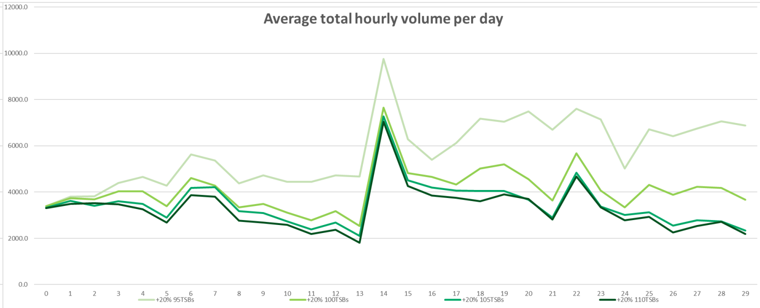

Figure 5.26: Daily average hourly total volume to be handled for scenario 4, +20% demand of T1.

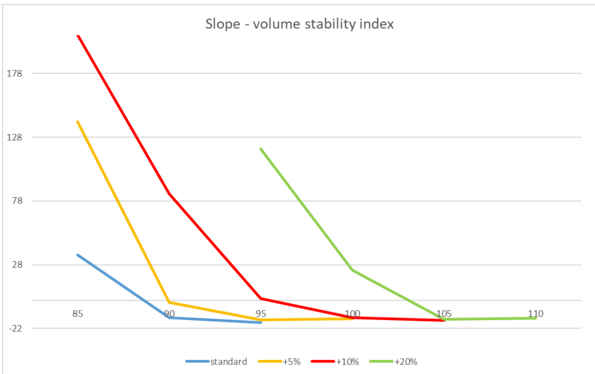

Figure 5.27: The slope index shows the stability of the demand, and spots if there is a storage buildup.

Figure 5.28 displays the average volume per terminal over the entire month. As previously described in 5.2.1, the volumes of T2 and T3 constitute a smaller portion of the total volume. Generally, the volumes of these external terminals are comparable across most settings. However, in scenarios where the system becomes overwhelmed and fails, an imbalance emerges.

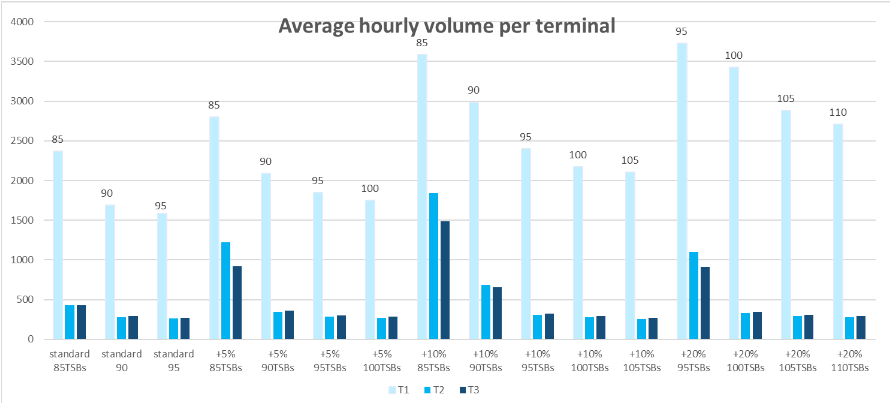

Figure 5.28: Average volume to be handled per terminal.

TSBs

Regarding the efficiency of TSBs, Figures 5.29 and 5.30 illustrate how an increase in vehicles may enhance the system's performance. However, this also leads to higher congestion, diminishing the efficiency of the additional units. As previously concluded in the analyses, when TSBs are added close to the minimum possible berth time, they do not significantly improve the system due to resource and infrastructure bottlenecks. This trend is evident in the figures, as the number of vehicles increases, the bigger the increase in waiting time is.

Volume T1	85	90	95	100	105	110
standard	25%	29%	31%			
+5%	26%	27%	31%	33%		
+10%	27%	28%	30%	33%	35%	
+10%			31%	32%	34%	37%

Figure 5.29: TSBs waiting times per scenario and number of TSBs used. The color range ranks the scenarios outputs from best (green) to worse performer (red).

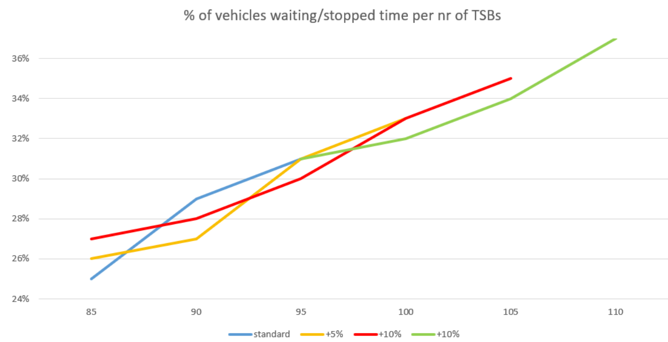

Figure 5.30: TSBs waiting time % per demand scenario and number of TSBs.

5.2.3. Modal share changes scenarios

For these scenarios, with modification on the modal shares, different number of operating TSBs are set:

- Standard: 85, 90 and 95
- +10% road / -10% rail: 90, 95 and 100
- +5% rail / -5% road: 80, 85, 90 and 95
- +5% ITT / -5% transshipment: 85, 90 and 95

Vessels

Berth time for these scenarios is depicted in 5.31 and graphed in 5.32. This clearly shows how the system handles more efficiently rail containers over road ones, which is very obvious do to the big difference in time it takes to go to the dry port compared to the terminal yard. It also shows how ITT containers are handled slightly worse than transshipment ones for the same reason, as they need to travel longer, some of them even more when they have to pass through the dry port for reaching the destination terminal. For this scenario, the buffer time at the external terminals was decreased from 14m12s to 12m22s because of the smaller share of containers going to the terminal yard from the berth.

Comparing the +10% road scenario to the base one it can be seen that for accommodating this modal share change, between five and ten extra vehicles are required.

Volume T1	80	85	90	95	100
standard		21.6	14.5	12.7	
+5%rail / -5%road	23.5	15.8	13.50	12.2	
+5% ITT / -5% transsh.		22.2	17	13.6	
+10%road / -10%rail			26.9	16.5	13.2

Figure 5.31: Median vessels berth times table per modal share scenario and number of TSB vehicles used. The color range ranks the scenarios outputs from best (green) to worse performer (red).

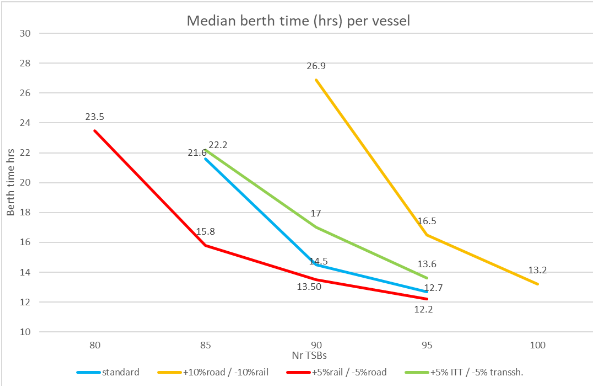

Figure 5.32: Median vessels berth times graph per scenario and number of TSB vehicles used.

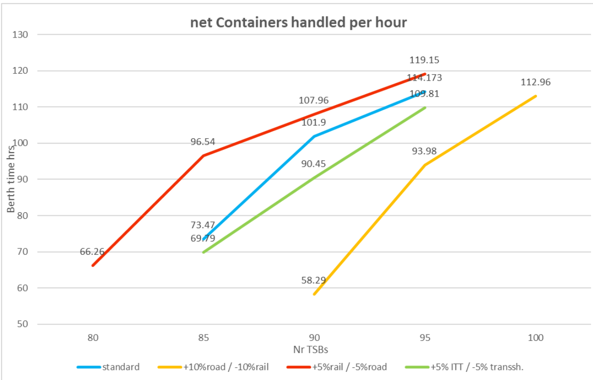

Figure 5.33: Net containers handled per hour per scenario and number of TSB vehicles used. Total containers/total berth time hours

Volume T1	80	85	90	95	100
standard		30.6	30.0	29.9	
+5%rail / -5%road	31.2	30.3	30.0	29.9	
+5% ITT / -5% transsh.		31.1	30.3	30.0	
+10%road / -10%rail			31.7	30.1	29.9

Figure 5.34: Schedule end time per scenario. Red cells represents scenarios in which the end time surpassed the maximum expected time, in which the vessels schedule starts to have a delay, meaning the system setup is not feasible to handle the scenario demand.

Volumes to be handled

Figure 5.35 displays the average total volume per day for all the different settings. Once again, the best performers are the scenarios with the minimum number of TSBs used per scenario, where the buildup can be clearly observed. While all scenarios follow the same trend based on the scheduled vessel volumes, there is a notable difference between the +10% road 90 TSBs scenario and the rest.

This difference arises due to a delay in the schedule, causing some vessels to wait for a berth space, resulting in delayed peaks compared to the other scenarios. The conclusions from these indicators are similar to the ones provided previously for the demand scenarios, and are therefore not discussed further in this section. However clearer views for each scenario, as well as the volumes division over the three terminals and the slope indexes, are provided in Appendix A.1.1.

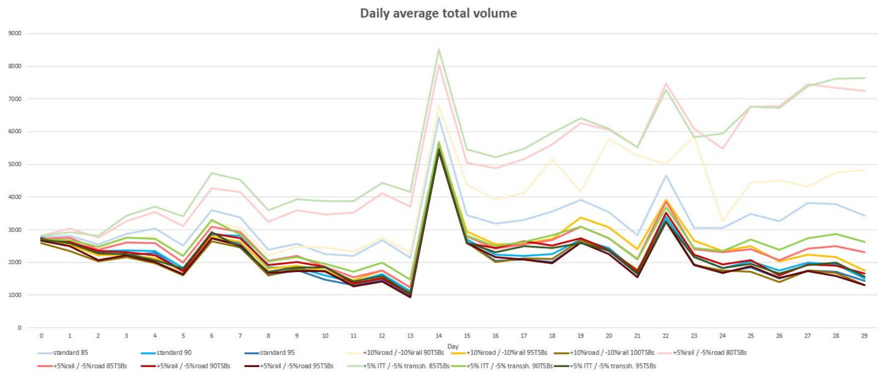

Figure 5.35: Daily average hourly total volume to be handled for all different scenarios.

TSBs

Figure 5.36 and 5.37 depict the percentage of TSBs experiencing stopped/waiting time per scenario. It is notable that there is a higher waiting time for the +5% rail scenario, attributed to the shorter distance to travel to the yard compared to the dry port, resulting in a lower proportion of time spent moving. Conversely, the lowest waiting time is observed for the +10% road scenario, followed by the +5% ITT scenario, due to similar reasons. Additionally, as highlighted in previous sections, an increase in the number of TSBs leads to increased congestion across all scenarios.

Volume T1	80	85	90	95	100
standard		25%	29%	31%	
+5%rail / -5%road	25%	26%	30%	33%	
+5% ITT / -5% transsh.		25%	26%	29%	
+10%road / -10%rail			26%	28%	31%

Figure 5.36: TSBs waiting time per scenario and number of TSBs used. The color range ranks the scenarios outputs from best (green) to worse performer (red).

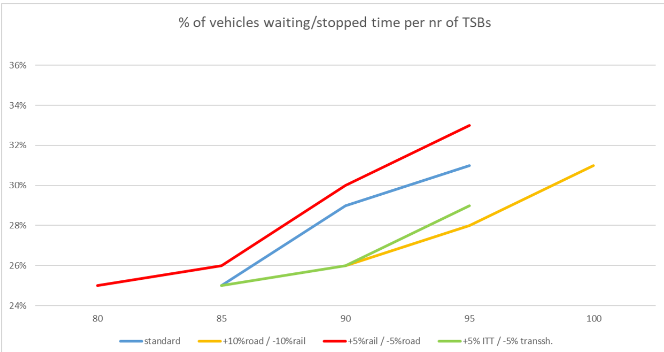

Figure 5.37: TSBs waiting time % per modal share scenario and number of TSBs.

Likewise, table 5.38 provides insights into the distance covered per TSB for the different scenarios. As anticipated, these results align with those obtained from the percentage of waiting times, with scenarios involving road and ITT increases exhibiting the highest covered distances.

Table 5.39 presents the average number of vehicles at terminal 1, reaffirming previous observations. Specifically, scenarios involving road and ITT increases result in vehicles departing the terminal earlier, owing to a higher rate of container pickups at the berth leading to vehicle departure. Conversely, the opposite trend is observed for the rail increase scenario.

Volume T1	80	85	90	95	100
standard		47257.3	44680.9	42472.2	
+5%rail / -5%road	48076.3	45393.1	42883.5	40731.2	
+5% ITT / -5% transsh.		50318.4	47653.7	45265.3	
+10%road / -10%rail			49544.6	46040.6	43723.6

Figure 5.38: Distance (in km) covered per TSB over the whole period. The color range ranks the scenarios outputs from best (green) to worse performer (red).

Volume T1	95
standard	26.97
+5%rail / -5%road	28.78
+5% ITT / -5% transsh.	24.70
+10%road / -10%rail	23.21

Figure 5.39: Average number of TSBs inside Terminal 1 for the scenarios with 95 vehicles.

5.3. Design 2: Shortcut connection around the port

This second design analysis corresponds to Design 2 (3.5).

The main setting standard demand scenario examination of this design employs, as in the previous Design, **90 TSB** Cargo trains to manage the entirety of container movement corresponding to current demand levels. The other scenarios were tested under different TSB vehicles settings between 80 and 100, as specified in Table 5.3.

Terminal 1

Main setting KPIs:

- Average berth time: 14.5h
- Median berth time: 12.6h
- Average containers/hr: 115
- Termination time: day 29.88

These vessel berth times mark a significant improvement over the benchmark of 0.79 days of median berth time, and is therefore considered a successful design.

Figure 5.40 presents a comparison of Terminal 1 container volumes over the simulation period between Design 1 and 2. These ones indicates a striking similarity in pattern, with Design 2 showing slightly lower volumes throughout most of the simulation duration. In the appendix, do to the similarity with Design 1, Figure A.1 displays the previous indicator categorized by import and export, and further divided according to their respective storage locations.

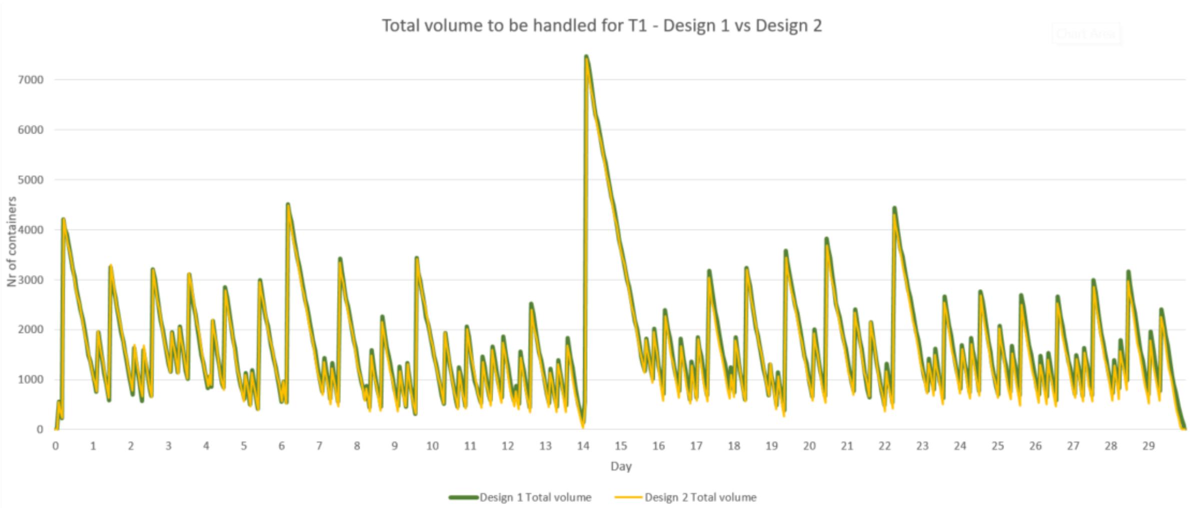

Figure 5.40: Comparison between Design 1 & Design 2 total volumes to be handled. A high resemblance is appreciated.

Design 2's marginal reduction in container volumes is reflected in the average berth times, with Design 2 exhibiting an improvement in average performance by nearly 2 hours (14.5h and 16.3h), as illustrated in Figure 5.41. This enhancement stems from the solitary modification between these designs: the introduction of a shortcut track linking the barge terminal and Terminal 2. Despite its seemingly minor impact, this track circumvents the need for vehicles to traverse the entire 20km distance to the Dry Port terminal unnecessarily. Particularly beneficial for Intra-Terminal Transportation (ITT) containers, this shortcut saves approximately 31.2km. While based on the ITT demand, only 11% of containers passing through the barge terminal opt for the shortcut to reach other port terminals, it is worth noting that this track is utilized in 13.5% of instances (10615 times compared to 67907 times for the track towards the dry port). Given the imbalance between export and import, there are frequently empty vehicles departing from or heading to a terminal for import container handling, while no more export containers are available from the dry port. Consequently, this track aids in balancing the load between terminals, mitigating unnecessary trips to the dry port and subsequent return trips with empty vehicles.

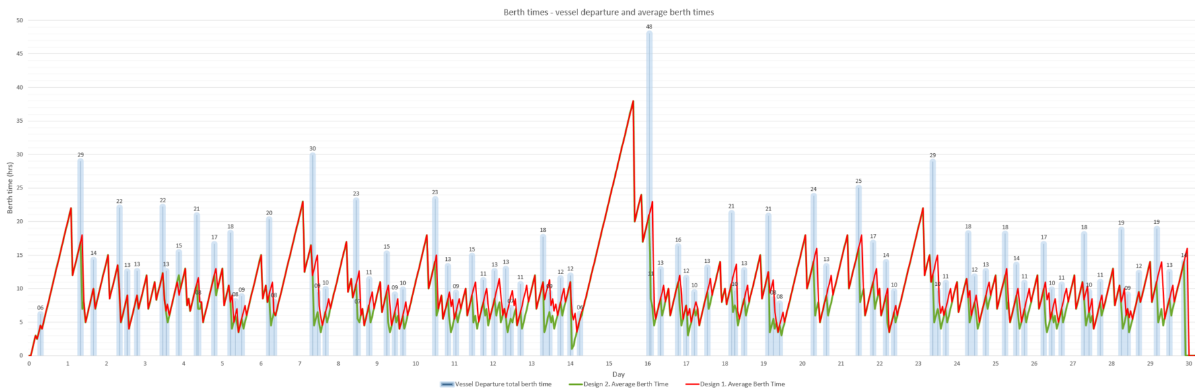

Figure 5.41: Vessels berth time by vessel's port departure depicted by the blue columns, the hourly average total berth time for Design 2 by the green line, in comparison with Design 1 in red.

Testing the design under the different demand scenarios, Figure 5.42 depicts the berth times for these, under different TSB vehicle settings, comparing Design 2 with Design 1. Similar to Design 1, initial increases in the number of vehicles lead to significant improvements in berth times in Design 2. However, as the number of TSBs approaches 95/100, the performance of quay cranes gradually reaches optimal levels, resulting in diminishing returns. Moreover, the increase in berth time increments becomes more pronounced with higher demand scenarios. For instance, for 95 vehicles, the transition from the standard to the +5% demand scenario results in a 1.9-hour increase, whereas transitioning from the +5% to +10% demand scenarios with 100 vehicles leads to a 4.1-hour gap. This trend highlights the bottleneck created by quay cranes at the berth under the current setting, suggesting that increasing the number of quay cranes alongside TSB vehicles is crucial for addressing higher volumes. A comparison of key performance indicators (KPIs) between Design 1 and 2 reveals an improvement of approximately 2 hours in performance. However, at higher volumes (e.g., +20% demand scenario), the bottleneck at the quay cranes is reached, resulting in comparable performances between the two designs.

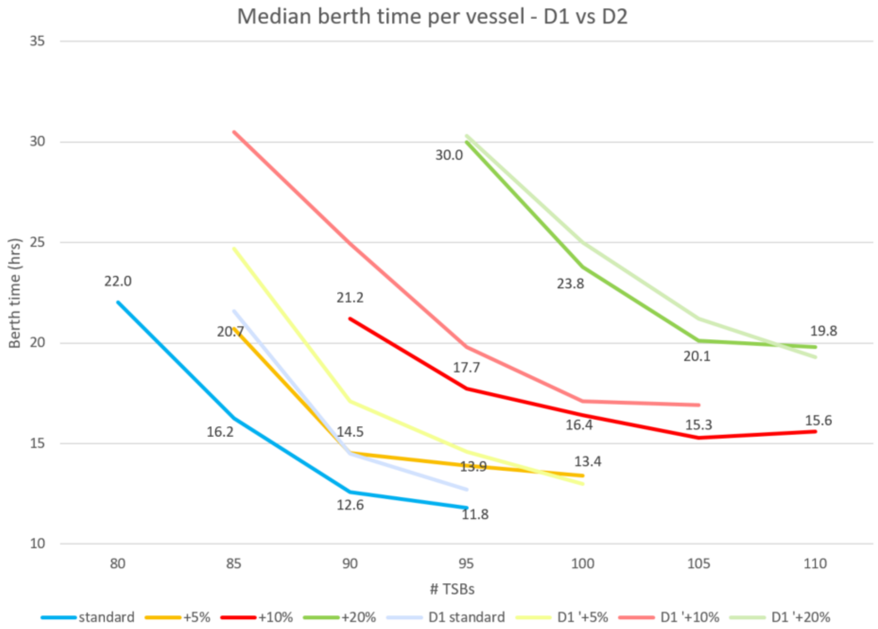

Figure 5.42: Median vessels berth times graph per demand scenario and number of TSB vehicles used. Unit: Hours.

Similarly, Figure 5.43 compares Design 2 with Design 1 for the modal share scenarios. The difference between the two designs is less pronounced for the +5% rail scenario compared to the +10% road scenario. This discrepancy is attributed to the shortcut track in Design 2, which generates more impact on dry port containers due to import-export imbalances, leading to empty trips to the dry port. The shortcut track also helps alleviate this imbalance by facilitating empty vehicle transfers between terminals. Additionally, the +5% ITT scenario benefits from shorter travel distances for trips between terminals 1-2, 3-2, and 3-1 (in this origin-destination order). Appendix A.1.2 contains Figure A.7, plotting the number of net containers handled per hour for all scenarios, which directly correlates with berth times. Simulation end times, as seen in Appendix A.8, are highly similar to those of Design 1 and align with the slope index (see Appendix Figure A.19), indicating delayed end times due to container build-up.

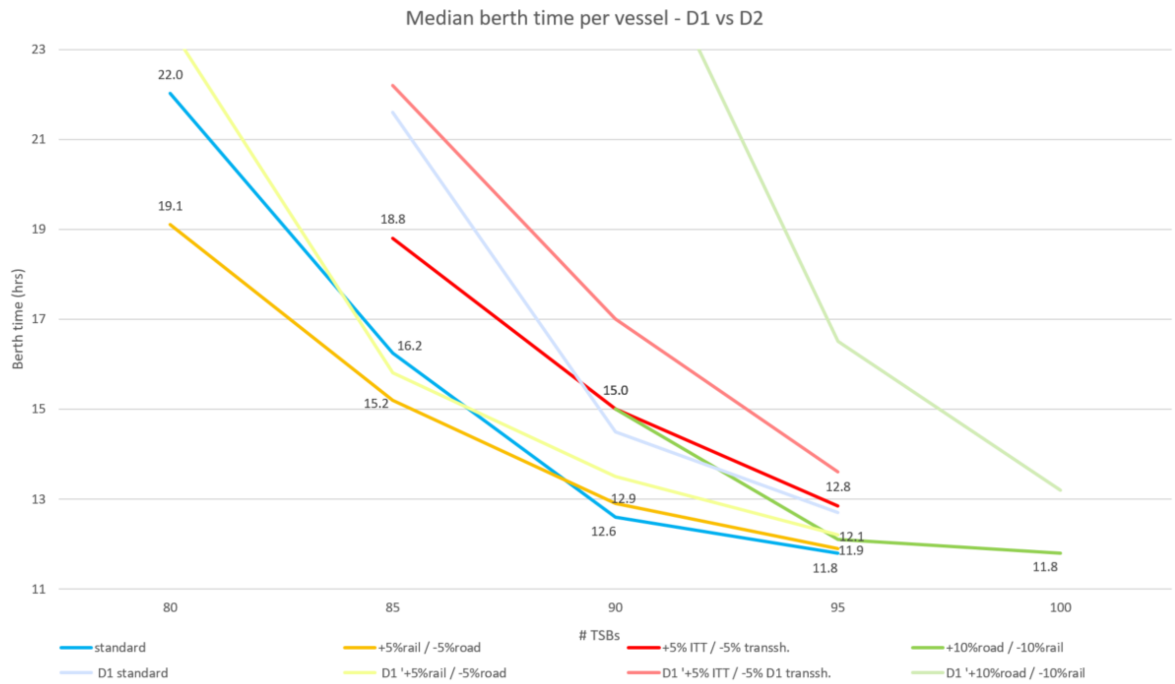

Figure 5.43: Median vessels berth times graph per modal share scenario and number of TSB vehicles used. Unit: Hours.

External terminals
Similarly, in line with Terminal 1 volumes, Figure 5.44 shows the volumes for external terminals, underscoring the striking resemblance between Designs 1 and 2, with Design 2 volumes occasionally slightly higher or lower. The average volumes for the two designs are also very close, at 285 and 294, respectively. The marginally higher volumes observed in Design 2's external terminals can be attributed to the assignment of empty vehicles facilitated by the shortcut track, which tends to dispatch vehicles to T1 when necessary. In contrast, in Design 1, an empty vehicle arriving at the Dry Port has a higher likelihood of being directed towards T2 or T3 when Dry Port export containers are unavailable for T1.

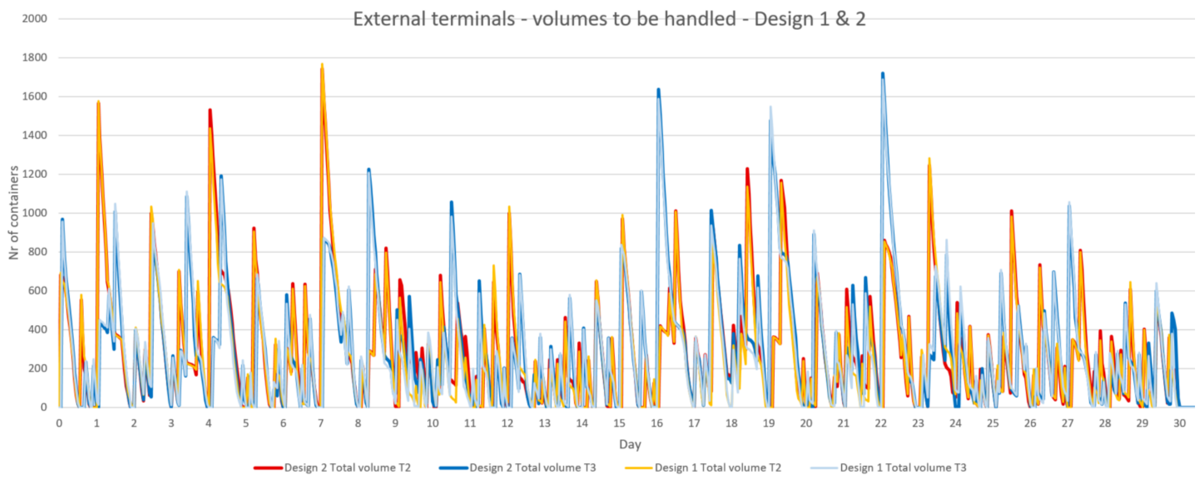

Figure 5.44: External terminals (T2 and T3) volumes to be handled per hour. Comparison for Design 1 and Design 2.

All terminals
Overall, examining the total volumes across all three terminals, Figure 5.45 illustrates the average total container volume per day for the main TSB settings of each demand scenario in Design 2. These scenarios exhibit controlled volumes without significant build-up, similar to Design 1. Daily average volume graphs for the remaining scenarios, as well as the volumes divided by terminals for the main

setting, can be found in Appendix A.1.2, but are not discussed further in this section due to their similarity to Design 1.

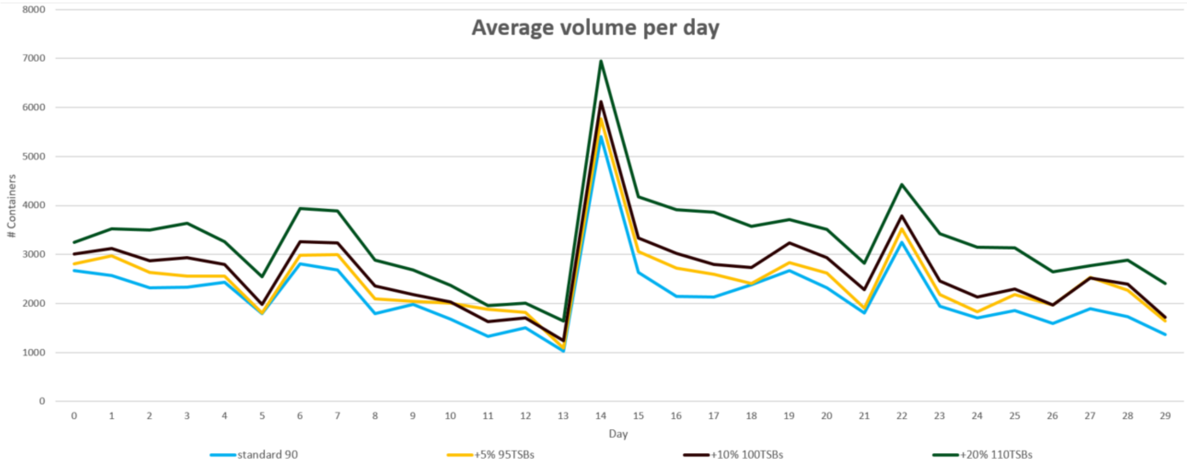

Figure 5.45: Daily average hourly total volume to be handled for all different scenarios.

TSB vehicles

Concerning the utilization of TSB vehicles, Table 5.46 presents their Key Performance Indicators (KPIs). In comparison to Design 1, the average distance covered per TSB is slightly lower (41749 vs 44681 km), primarily due to the distance savings realized by eliminating unnecessary travel to the dry port. Another discernible difference compared to Design 1 is a slightly higher percentage of waiting/stopped time (31% vs 29%). This uptick can be attributed to a slightly higher concentration of vehicles at the terminals, resulting from reduced travel distances and enhanced resource efficiency, albeit with increased waiting times. Additionally, as travel time decreases, the share of stopped time increases accordingly.

Moreover, Figure 5.47 plots the percentage of TSB vehicles in waiting/stopped status for the different scenarios and TSB settings. For each scenario, adding more vehicles beyond a certain threshold leads to a proportional increase in congestion without offering substantial benefits. The scenario with increased ITT share exhibits the lowest waiting time, as vehicles spend less time at Terminal 1, where congestion is primarily located.

Nr TSB vehicles	90
Avg. covered Distance per TSB (kms)	41749.5
% moving time	49%
% waiting/stopped time	31%
% time at external terminals	21%
% time empty	14%
total Simulation moves (#)	237929

Figure 5.46: TSB statistics for 90 vehicles. Distance in km.

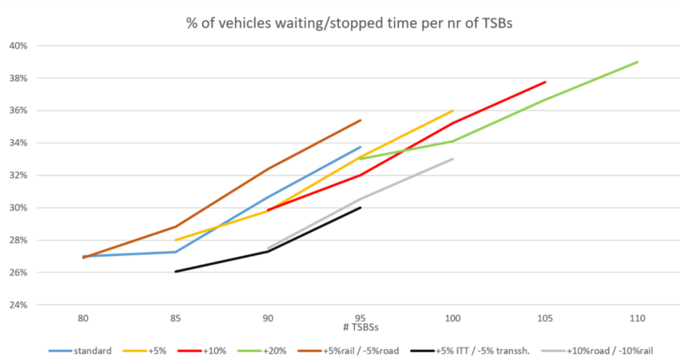

Figure 5.47: TSBs waiting time % per modal share scenario and number of TSBs.

Cranes

In terms of resources, the lowered berth times signify increased efficiency of the quay cranes, evidenced by an average increase of 3.2 moves per hour per QC (28.7) and a 7% (64%) increase in net working time (see Figure 5.48). The usage of yard and dry port RMGs remains unchanged, as the total simulation time and volumes handled are consistent across both designs.

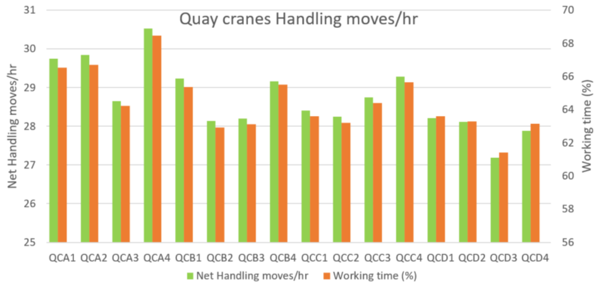

Figure 5.48: Quay cranes net productivity and net handling moves per hour.

5.4. Design 3: Double track

The third design analysis corresponds to Design 3 (3.7).

This main setting centers on the standard demand scenario, utilizing 95 TSB Cargo trains to accommodate the total container movement associated with current demand levels. A higher number of vehicles is needed for this setting, so **95 vehicles** are used instead of the 90 used in the previous reference designs.

Terminal 1
Main setting KPIs:

- Average berth time: 18.9h
- Median berth time: 17h
- Average containers/hr: 88.2
- Termination time: day 30.05

These vessel berth times surpass the established benchmark of 0.79 days of median berth time (18.96 hours), confirming the design's approval.

Figure A.21 illustrates the volumes to be managed for Terminal 1, both import and export, categorized by their respective storage locations. A comparison of real-time total volumes between Designs 1 and 3, as shown in Figure 5.49, reveals lower performance in Design 3, with volumes consistently higher than those in Design 1. In the appendix, Figure A.21, closely resembling the respective figure of Design 1, depicts these T1 volumes categorized by their respective storage locations.

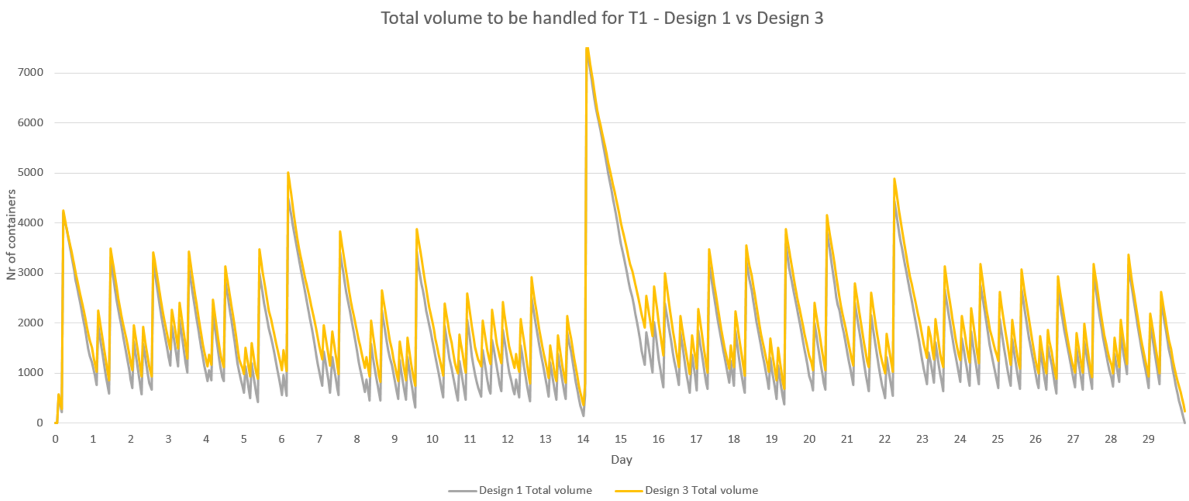

Figure 5.49: Comparison between Design 1 & Design 3 total volumes to be handled.

The increase in volumes in Design 3 is reflected in higher berth times, with Design 3's berth time averaging 2.6 hours longer (18.9 hours compared to 16.3 hours in Design 1). This difference is illustrated in Figure 5.50, where it is evident that berth times increased in 97.5% of the vessels.

Initially, two primary objectives drove the development and testing of this design with a double track: to enhance the system's resilience and enable container loading and unloading on two tracks simultaneously. However, despite achieving these goals, the performance of berth times worsened, even with 5 additional TSB vehicles. The congestion generated at the terminals is the main contributing factor to this deterioration. In Design 1, there were 2 tracks at the terminal, one dedicated to serving the berth and another functioning as a fast track for vehicles that did not require loading or unloading containers at the terminal. With the implementation of the double track design and the performance of vessel loading operations on both tracks, the 'fast-track' was eliminated. Consequently, all vehicles, regardless of their destination, had to contend with queuing and congestion at the berths of the four different terminals (T1, T2, T3, and the barge terminal). This led to reduced vehicle efficiency, resulting in longer travel times to destinations and decreased productivity of (un)loading operations.

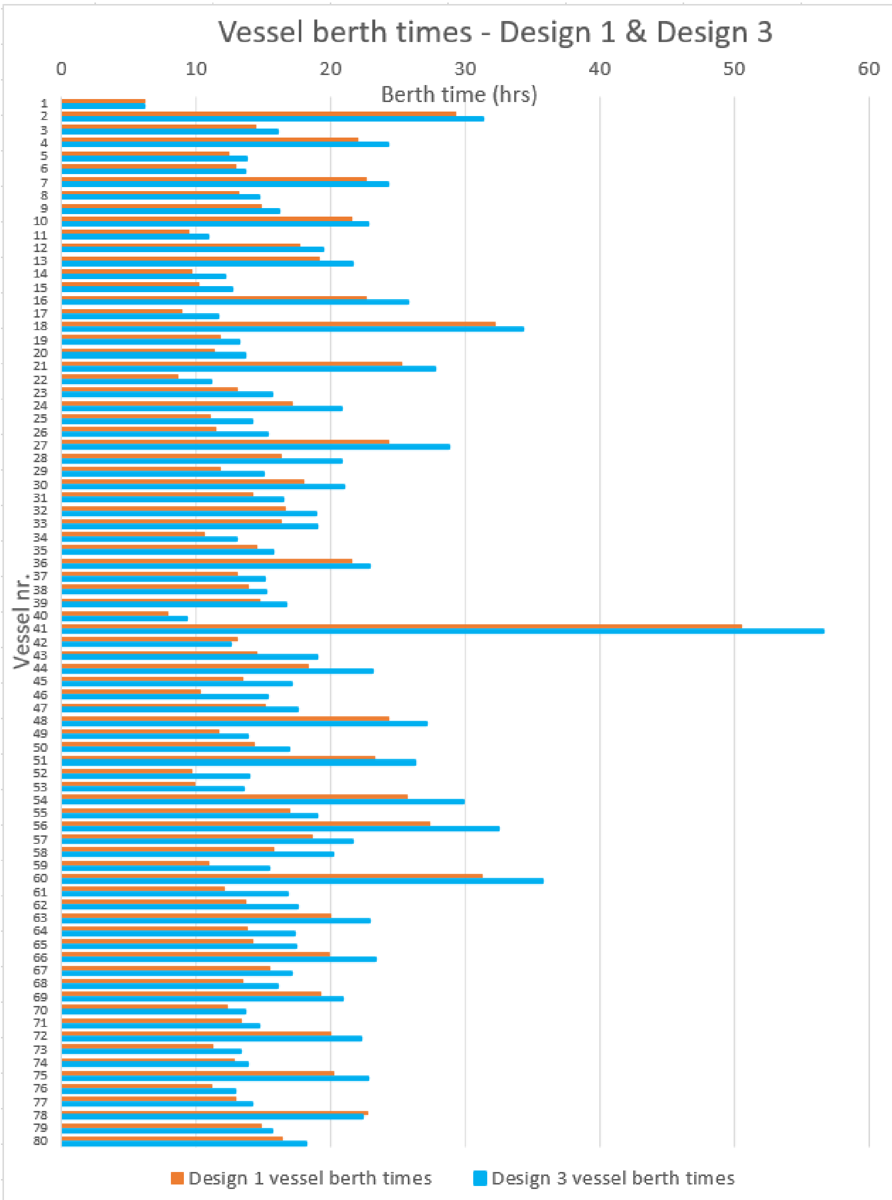

Figure 5.50: Vessels berth time comparison between Design 1 and 3. Orange bars represent Design 1's vessel berth times and blue ones Design 3.

Figure 5.51 presents the berth time for the different demand scenarios under the different number of TSB vehicle settings, in comparison to Design 1. The impact of vehicle increase follows a similar pattern as Design 1, with an addition of a couple of hours. However, the difference between the +10% and +20% demand scenarios is smaller for Design 3 than for Design 1, indicating that Design 3 allocates volume increases more efficiently due to its capacity for (un)loading on two tracks simultaneously, transferring the negative effect of an increased congestion to the external terminals.

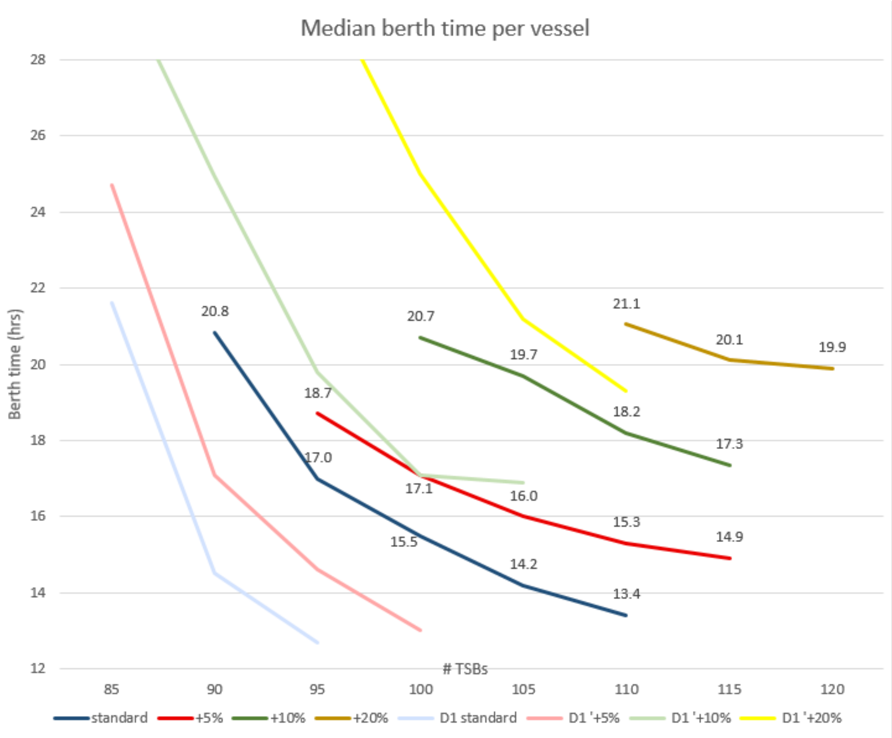

Figure 5.51: Design 3 comparison with Design 1 (D1). Median vessels berth times graph per demand scenario and number of TSB vehicles used. Unit: Hours.

Similarly, Figure 5.52 compares Design 1 and 3 for the modal share scenarios. Again, it can be seen that the performance difference between scenarios is smaller for Design 3. This is because the higher congestion in Design 3 allows the system to reach its optimal performance faster, mitigating the impact of scenarios that would be worse for the system. As in the previous designs, the rail increase scenario performs the best, followed by the base scenario, while the ITT and road scenarios perform very similarly.

Appendix A.1.3 provides additional graphs related to berth performance, including containers handled per hour, end times, and volume slopes, which are not discussed here as they follow the same trends as previous designs. **External terminals**

Similar to Terminal 1 volumes, Figure 5.53 highlights the resemblance between Designs 1 and 3, with Design 3 exhibiting higher volumes at most times. This increase is attributed to congestion-induced efficiency losses, resulting in fewer vehicles arriving at terminals per hour to serve containers.

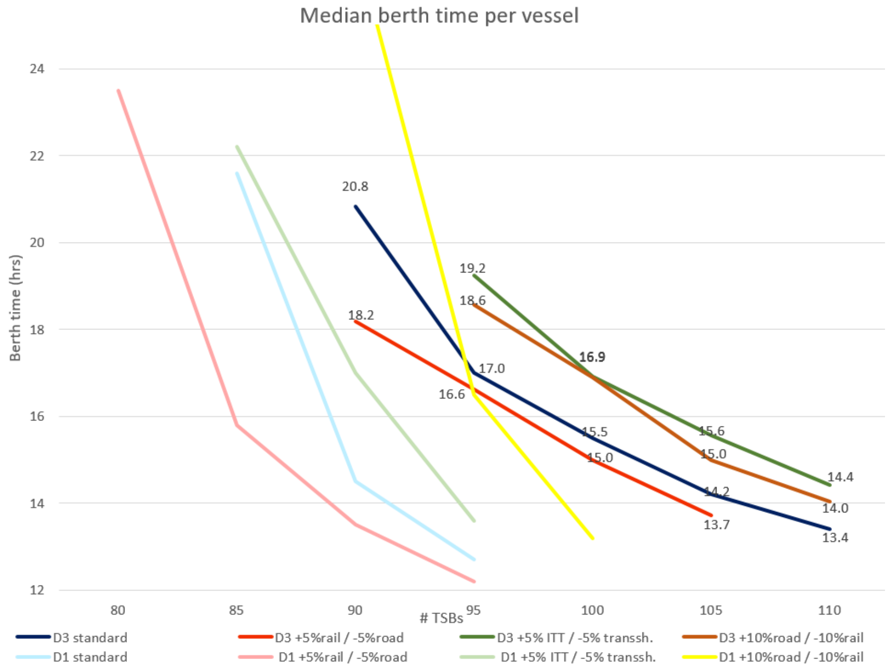

Figure 5.52: Design 3 comparison with Design 1 (D1). Median vessels berth times graph per modal share scenario and number of TSB vehicles used. Unit: Hours.

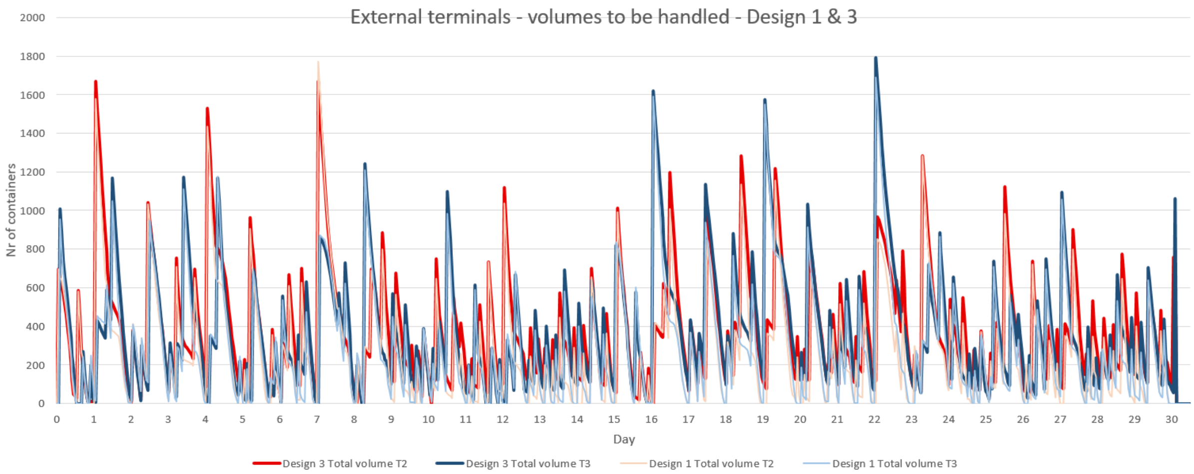

Figure 5.53: External terminals (T2 and T3) volumes to be handled per hour. Comparison for Design 1 and Design 3.

All terminals

Figure 5.54 shows the average total container volume per day for the main TSB settings of each demand scenario. These scenarios perform well, showing controlled volumes that do not accumulate over time, despite the performance decline compared to Design 1. However, the +20% 115 TSBs scenario exhibits higher peaks and takes longer to reach valleys due to increased demands and lower efficiency. Similarly, in AppendixA.1.3 a similar figure for modal share scenarios can be found (A.30), in addition to comprehensive overview of volumes across all three terminals (5.54).

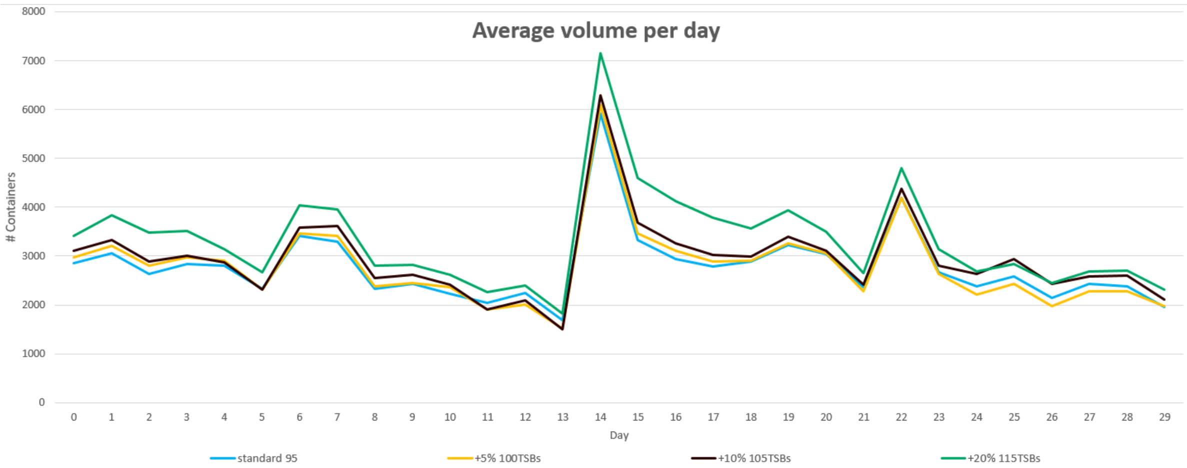

Figure 5.54: Design 3. Daily average hourly total volume to be handled for all different scenarios.

TSB vehicles

Regarding the usage of TSB vehicles, Table 5.55 presents key performance indicators (KPIs). Compared to Design 1, Design 3 covers a lower total distance (3725571 km vs. 4021280 km), primarily due to distance savings from avoiding unnecessary travel to the dry port. Additionally, Design 3 exhibits a slightly higher percentage of waiting/stopped time (31% vs. 29%), attributed to increased berth congestion. Additionally, the time spent at external terminals also increased from 21% to 26%, however this is not counted as waiting time because these terminals are modelled as black boxes, so there is no congestion calculated.
Figure 5.56 plots the TSB vehicles' waiting/stopped time percentage for the different scenarios. Consistent with previous conclusions, the rail increase scenario exhibits the highest waiting time percentage due to its higher performance and the increased average number of vehicles at terminal 1 (20.4 for the rail increase and 19.1 for the standard demand scenario).

Nr TSB vehicles	95
Avg. covered Distance per TSB (kms)	39216.5
% moving time	46%
% waiting/stopped time	28%
% time at external terminals	26%
% time empty	12%
total Simulation moves (#)	238364

Figure 5.55: TSB statistics for 95 vehicles. Distance in km.

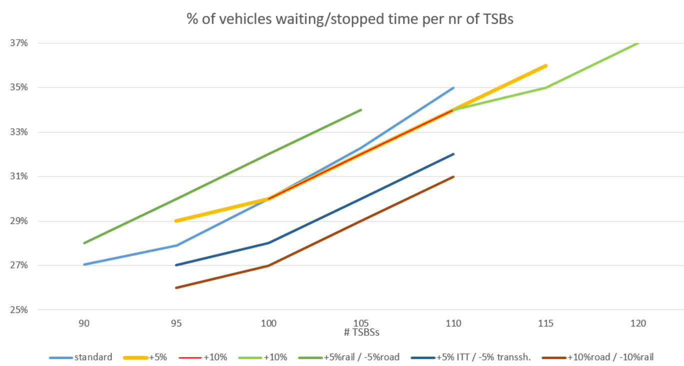

Figure 5.56: Design 3. TSBs waiting time % per modal share scenario and number of TSBs.

Cranes

Analysis of resources reveals decreased efficiency of quay cranes in Design 3, with an average decrease of 3.35 moves per hour (22.1 moves per hour) and a 7% decrease in net working time (50% compared to 57% in Design 1), as shown in Figure 5.57.

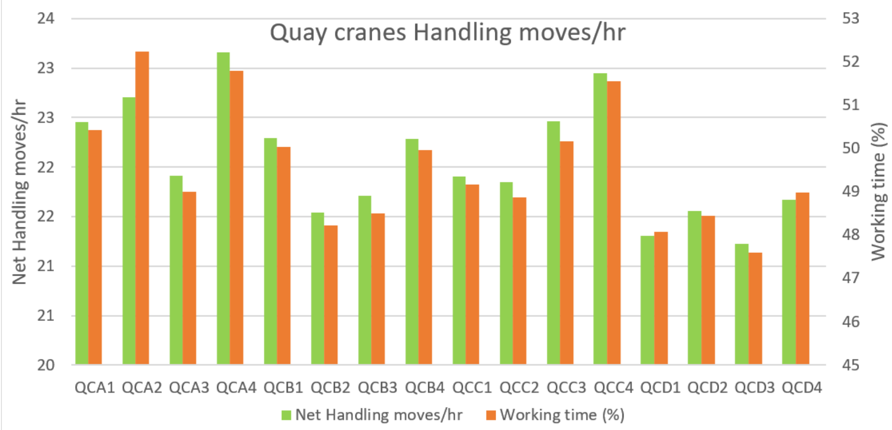

Figure 5.57: Design 3. Quay cranes net productivity and net handling moves per hour.

5.5. Design 4: Extra switches at berth

The fourth design analysis corresponds to Design 4 (3.22).
Design 4's main setting analysis is done for the standard demand and with 90 TSB Cargo trains, to handle the full container transport of all terminals for the current inputted demand.

Terminal 1

- Average berth time: 15.7h
- Median berth time: 13.5h
- Average containers/hr: 105.8
- Termination time: day 29.99

The vessel berth times showcase an advancement from the benchmark of 0.79 days of median berth time (18.96 hours), again affirming the success of the design.

The performance of Design 4 falls between Design 1 and Design 2, with Design 2 being the best-performing design. In terms of handling terminal 1 containers, there is a high resemblance to the main design (Design 1), with volumes sometimes slightly higher and other times lower, but overall having lower volumes (78.5 on average), as depicted in Figure 5.58.

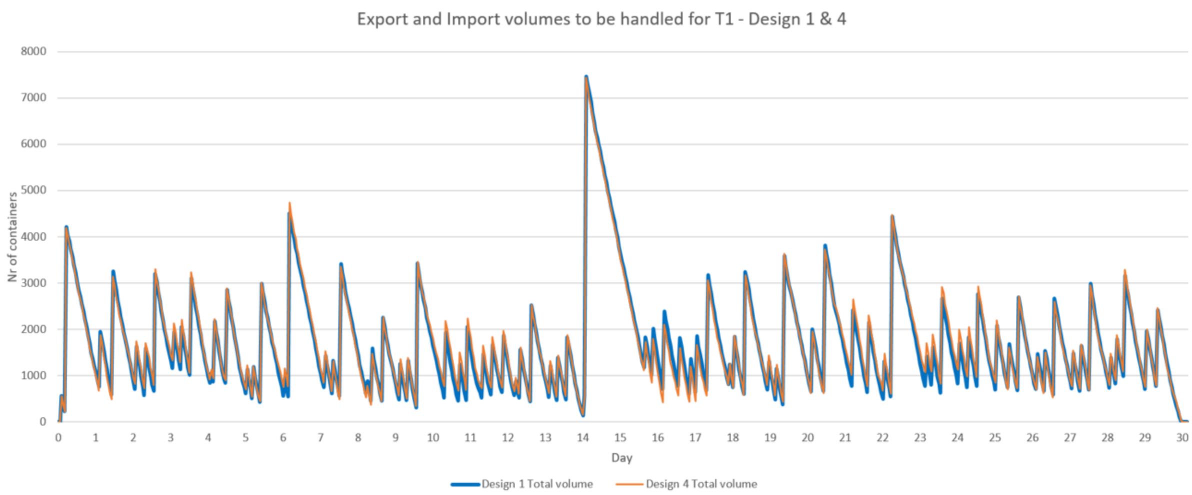

Figure 5.58: Comparison between Design 1 & Design 4 total volumes to be handled. A high resemblance is appreciated.

The reduction in volumes is later slightly appreciated in the average berth times, with Design 4 improving performance by almost 0.6 hours (15.7h and 16.3h). This improvement is depicted in Figure 5.59, which shows how berth times are enhanced for 61 out of the 80 vessels of the inputted monthly schedule. A deeper analysis is presented in Figure 5.60, illustrating the average berth time reduction per berth space. It is noteworthy that none of the berths experience a decline in performance on average due to these design changes.

Berths 1 and 2 exhibit the lowest improvements for specific reasons. Particularly, berth 1, being the first berth, sees fewer benefits from the extra switches since no vehicles make use of them initially. Similarly, berth 2 sees lower improvements because vehicles only use the extra switches if there are vehicles being (un)loaded at berth 1. Conversely, berth 3 shows the most significant improvement over berth 4. This is attributed to the assignment of the fast track for the use of the shortcut switches. In many cases, vehicles may use the fast track to bypass congestion at previous berths. However, upon arrival at berth 4, these vehicles may find that those in front have already completed their operations, nullifying the advantage of taking the shortcut. Surprisingly, berth 1, which was expected to be disadvantaged due to coping with more vehicles in front after finishing loading operations, experiences the opposite. Vehicles at the shortcut switches wait for vehicles already finished with their operations before passing, resulting in less congestion for earlier berth vehicles after (un)loading.

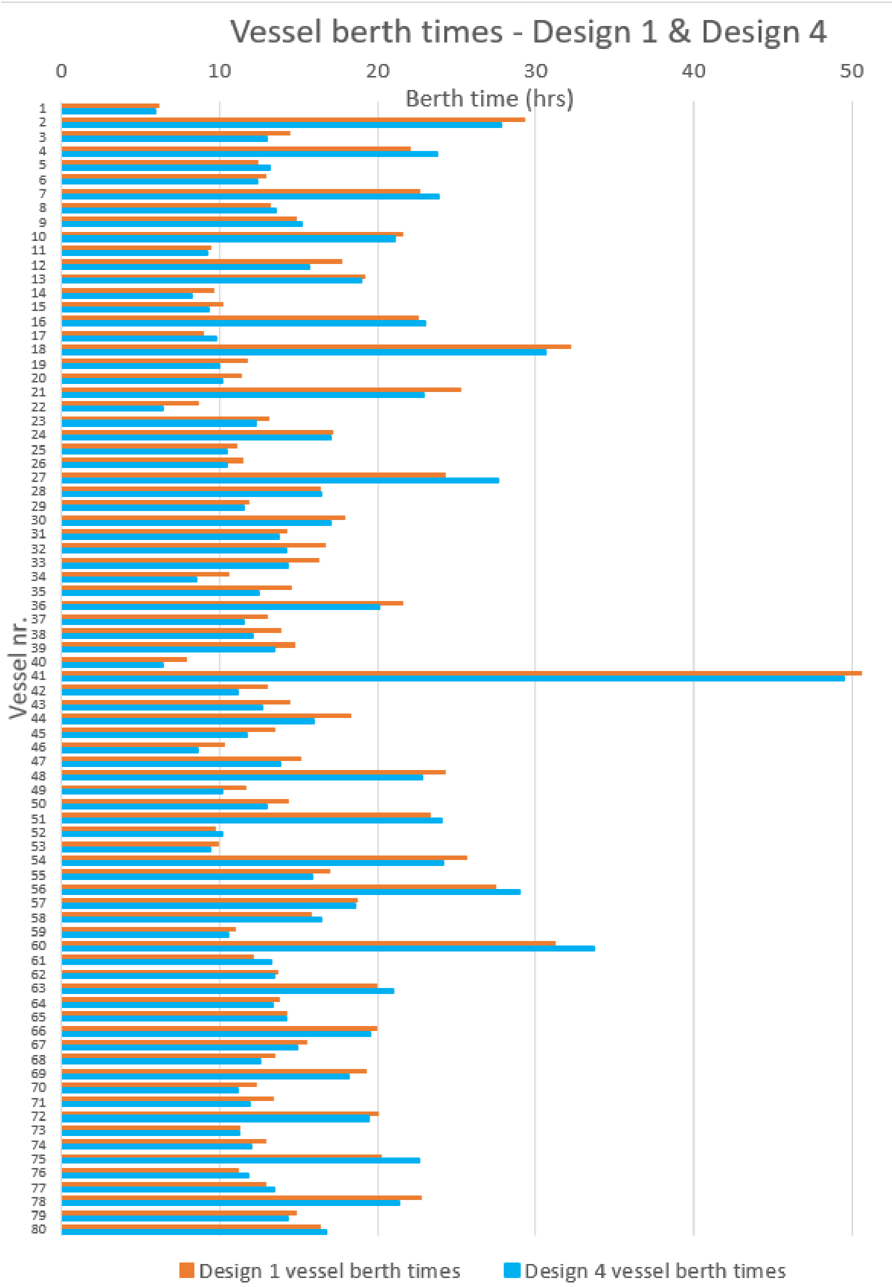

Figure 5.59: Vessels berth time comparison between Design 1 and 4. Orange bars represent Design 1's vessel berth times and blue ones .

BerthNr	Average berth time reduction (hrs)
1	0.34
2	0.37
3	1.18
4	0.49

Figure 5.60: Average vessels berth time reduction from Design 1 to Design 4 per berth location (1 to 4).

Figure 5.61 presents the berth time for the different demand scenarios under the various number of TSB vehicle settings, comparing them to those of Design 1. Notably, for higher demand volumes, the increase in vehicles barely affects the performance compared to Design 1. Moreover, it is observed that for a high number of vehicles, the berth time results are almost identical for Design 1 and Design 4.

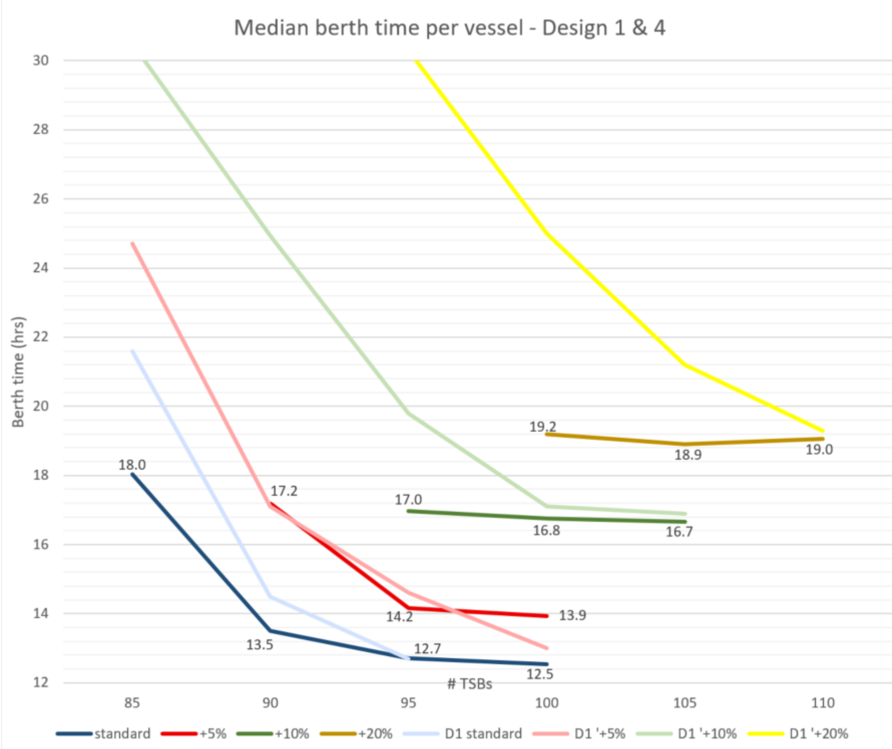

Figure 5.61: Design 4 comparison to Design 1. Median vessels berth times graph per demand scenario and number of TSB vehicles used. Unit: Hours.

Similarly, Figure 5.62 compares the two designs for the modal share scenarios. Once again, the differences between scenarios are minimized when reaching 95 or 100 TSB vehicles. It's worth mentioning the similarity in performance for the rail increase scenario between both designs. Additional related figures can be found in Appendix Figure A.1.4.

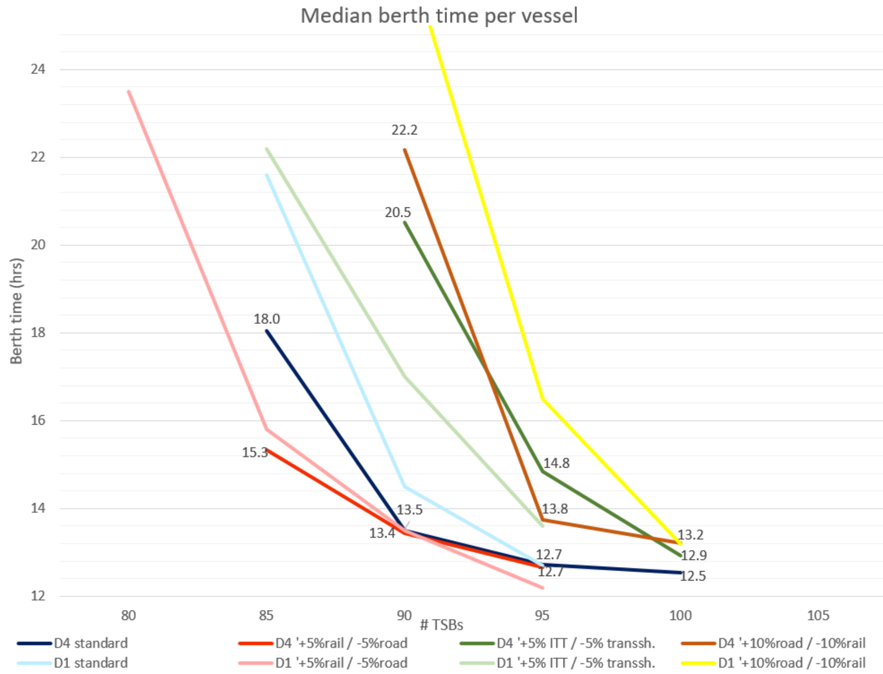

Figure 5.62: Design 4 comparison to Design 1. Median vessels berth times graph per modal share scenario and number of TSB vehicles used. Unit: Hours.

External terminals

Similarly, Figure 5.63 shows the resemblance between Designs 1 and 3 regarding external terminal volumes, with Design 2 volumes sometimes slightly higher and sometimes slightly lower. On average, external terminal volumes are slightly higher for Design 4, mainly due to delays in the fast track at terminal 1 caused by shifts in switches, slowing down vehicle paths.

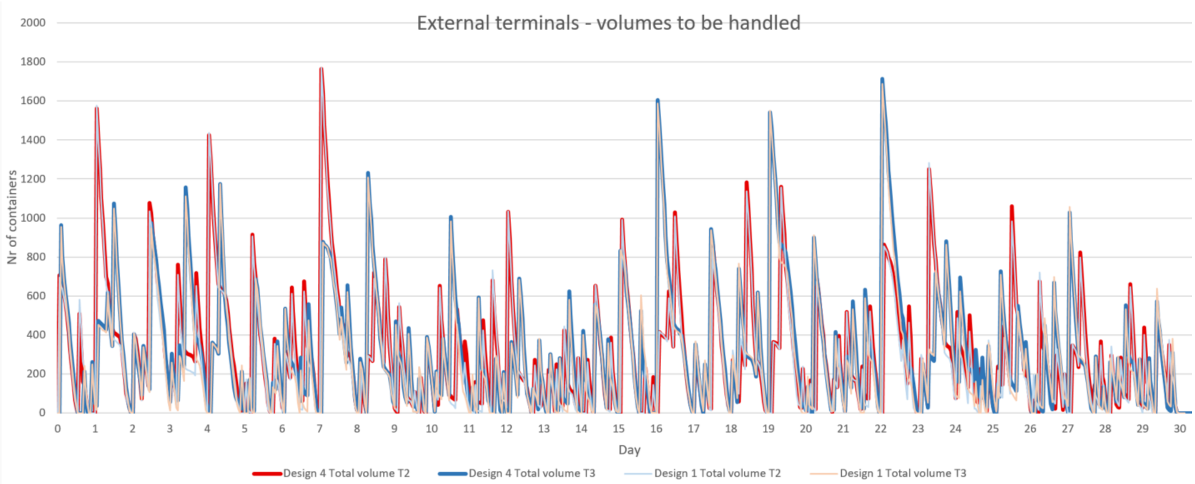

Figure 5.63: External terminals (T2 and T3) volumes to be handled per hour. Comparison for Design 1 and Design 4.

All terminals

Figure 5.22 illustrates the average total container volume per day for the main TSB settings of each demand scenario. These volumes are very similar to those of Design 1, and even more so to Design 2, demonstrating a well-performing system where volumes don't accumulate, making them successful designs. The daily average volumes for the remaining scenarios and their division between terminals can be found in Appendix A.1.2, with no further discussion in this section due to the similarity with Design 1 and previous discussions.

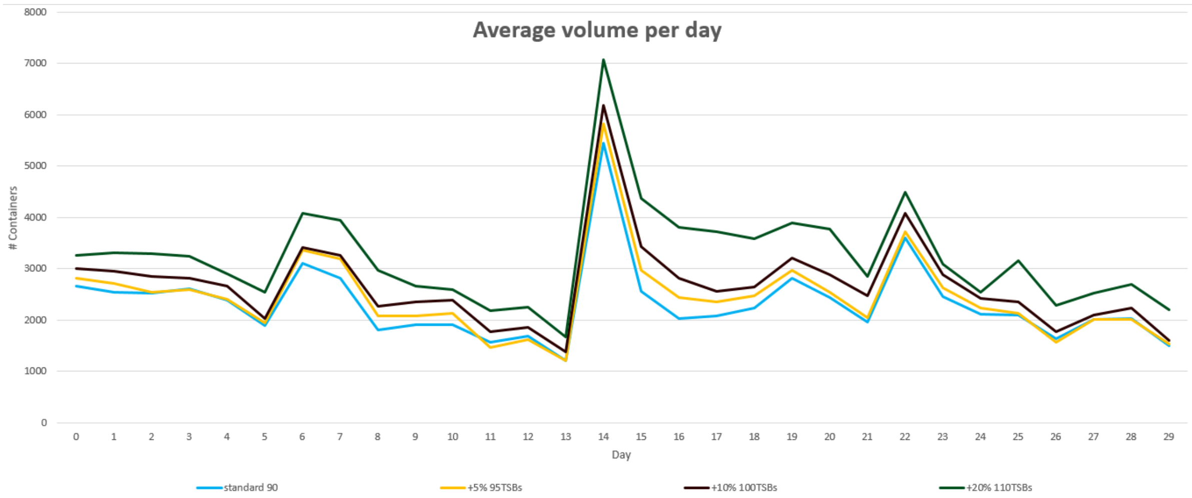

Figure 5.64: Design 4 main vehicle settings of demand scenarios. Daily average hourly total volume to be handled.

TSB vehicles

Regarding the usage of TSB vehicles, Table 5.65 presents their KPIs. Compared to Design 1, the average covered distance per TSB is very similar (44615 and 44681 km for Design 1), but the percentage of time spent waiting or stopped while waiting for loading operations, congestion, or switches decreases in Design 4 by 3% (28%). This is attributed to decreased congestion at terminal 1, as previously discussed. More information related to the TSB vehicles performance, including the demand and modal share scenarios, can be found in Appendix A.1.2, showing a high similarity with Design 2.

Nr TSB vehicles	90
Avg. covered Distance per TSB (kms)	44614.7
% moving time	51%
% waiting/stopped time	28%
% time at external terminals	21%
% time empty	14%
total Simulation moves (#)	237929

Figure 5.65: TSB statistics for 90 vehicles. Distance in km.

Cranes

In terms of resources, the efficiency of quay cranes is increased in Design 4 due to lower berth times, with an average increase of 1 extra move per hour (26.4) and a 4% (61%) increase in net working time compared to Design 1 (see Figure 5.66).

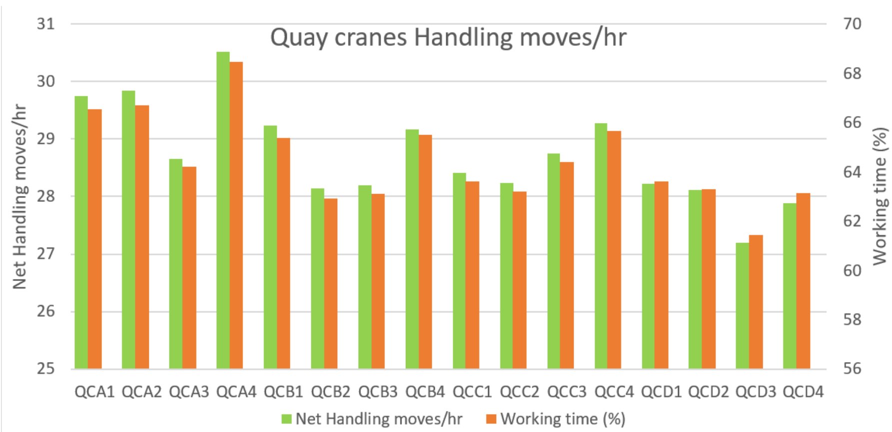

Figure 5.66: Design 4. Quay cranes net productivity and net handling moves per hour.

5.6. Design 5: No intra-terminal transportation

The fifth and last design analysis corresponds to Design 5 (3.23).

The main setting analysis is conducted for the standard demand with **70 TSB** cargo trains to fulfill the entire container movement of the current demand. This lower number of vehicles is used because only ITT, barge, and dry port containers of Terminal 1 are handled with TSBs, as intra-terminal transportation is done with AGV vehicles. Therefore, the volume handled for Terminal 1 is 45,348 containers, which accounts for 25% of the total Terminal 1 handling moves. Consequently, the total system TSB moves are reduced by 20%.

The demand and modal share scenarios were tested under different TSB vehicles settings between 65 and 80, as specified in Table 5.3. The +5% ITT / -5% transshipment scenario was excluded from testing in this design because intra-terminal operations are not modeled, resulting in minimal impact on the system.

Terminal 1 Main setting KPIs:

- Average berth time: 14.2h
- Median berth time: 11h
- Average containers/hr: 117.2
- Termination time: day 29.97

The achievement in vessel berth times, exceeding the benchmark of 0.79 days of median berth time (18.96 hours), validates the success of the design in meeting operational objectives.

Figure 5.67 presents the total volumes to be handled for Terminal 1, both import and export, divided by their two transportation modes: TSBs and AGVs. It's evident that TSB volumes are significantly lower than AGV volumes, comprising only 12.5% of the total volume on average. This percentage is lower than the actual 25% of the volume that TSB handles for Terminal 1. The reason for this discrepancy can be observed in the figure: TSB volumes are generally processed first, resulting in a steep decrease in volumes. In contrast, AGV volumes are handled continuously, with a high frequency of arrivals when vessel containers are being processed. When TSBs arrive, the frequency of AGV operations decreases until the TSB containers are fully handled, after which TSB operations speed up again. There is still a reduction in volumes during TSB operations, but the decrease is less steep. This is because, in this simulation, TSBs have priority over AGVs, with AGV operations being performed only when no TSBs are being handled at the respective berth. It's notable how TSB volumes quickly reach zero, allowing for a shift in focus to other terminals and freeing up space in the berth for AGVs.

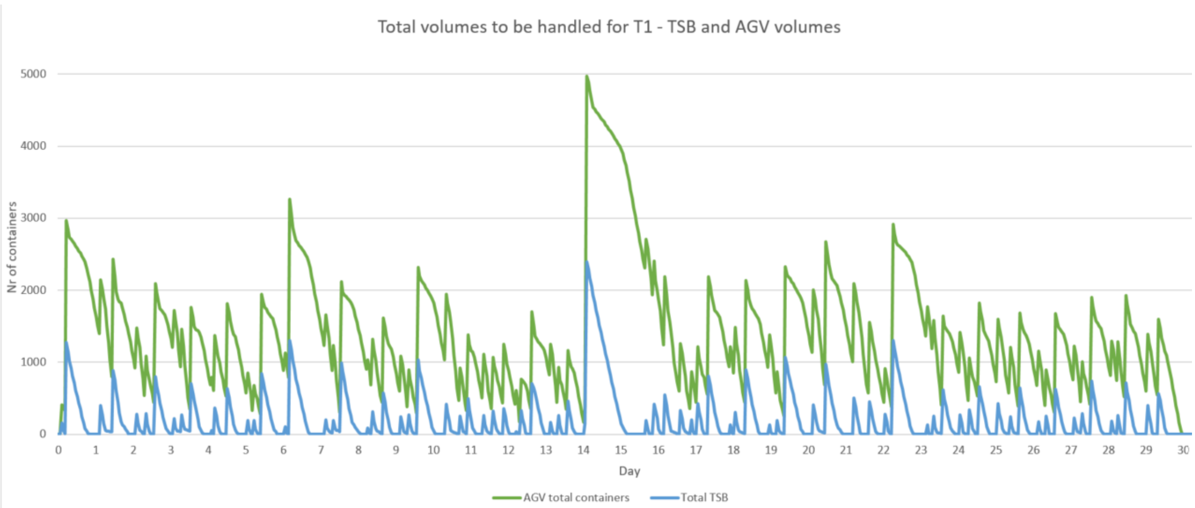

Figure 5.67: Comparison volumes to be handled with AGVs and TSBs over the simulation period. As the container is handled the volume decreases, therefore low levels are preferred. Volumes increase at vessel arrivals.

Figure 5.68 compares the real-time total volumes with Design 1, revealing more differences compared to previous designs. While both designs follow a similar pattern, there are notable variations. Design 5 performs better during lower peaks, showing a steeper reduction in volumes. However, during higher peaks, the opposite occurs, with Design 5 averaging just 60 units lower (3.6%). This behavior is also reflected in Figure 5.69, which compares berth times between the two designs. For vessels with high volumes (resulting in high berth times), Design 5 exhibits higher berth times. Conversely, for vessels with low volumes, berth times are significantly decreased.

There are two reasons for this discrepancy. Firstly, low volume vessels tend to be less efficient due to operational factors. For instance, operations are less efficient at the beginning and end of vessel operations, as vessels that have been at the berth longer typically have priority for sending containers from the dry port. Additionally, fewer containers remaining towards the end of operations are harder to retrieve, further reducing efficiency. Conversely, in the integrated TSB+AGVs transportation system, AGVs are consistently available at the berth to handle vessels, regardless of their current times or remaining volumes, thus enhancing the efficiency of vessel operations.

However, for higher volume vessels, efficiency decreases do to the way the system is modeled. TSBs' operations work on a double-cycle basis, loading and unloading containers from the vessel simultaneously, while AGVs operations are modelled for a single-cycle. Double cycle operations are more efficient, taking 160 seconds for two container moves, while single cycle ones take 105 seconds for a single move. Consequently, despite increased working time efficiency of quay cranes, high volumes of AGV containers result in higher berth times in the long run.

Therefore, compared to Design 1, Design 5 achieves an average reduction of 1 hour in median berth time, with an average reduction of only 0.6 hours due to higher fluctuations in berth times. However, Design 5 still exhibits lower berth time performance than Design 2, with an average berth time 1.2 hours lower.

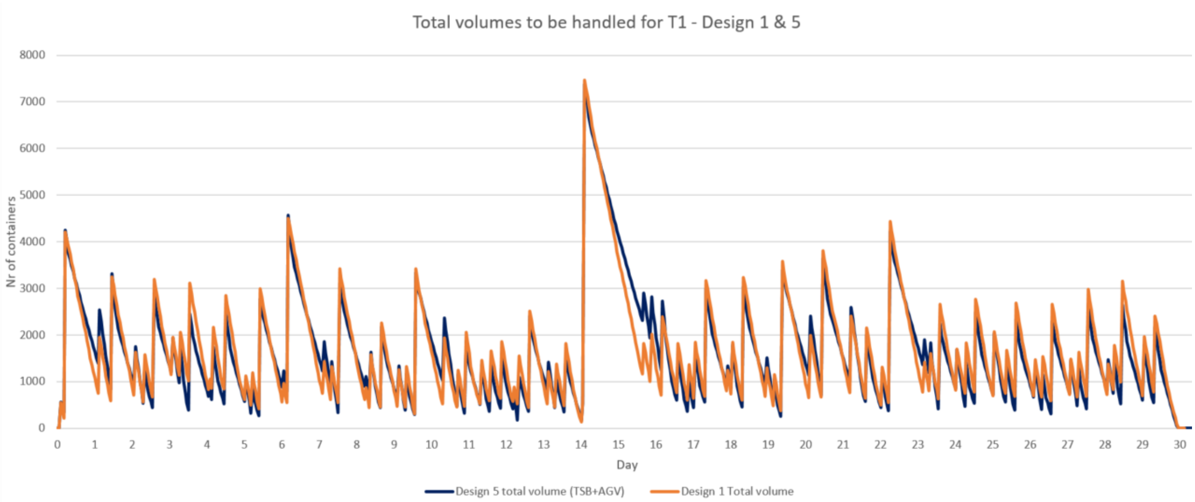

Figure 5.68: Comparison between Design 1 & Design 5 total volumes to be handled.

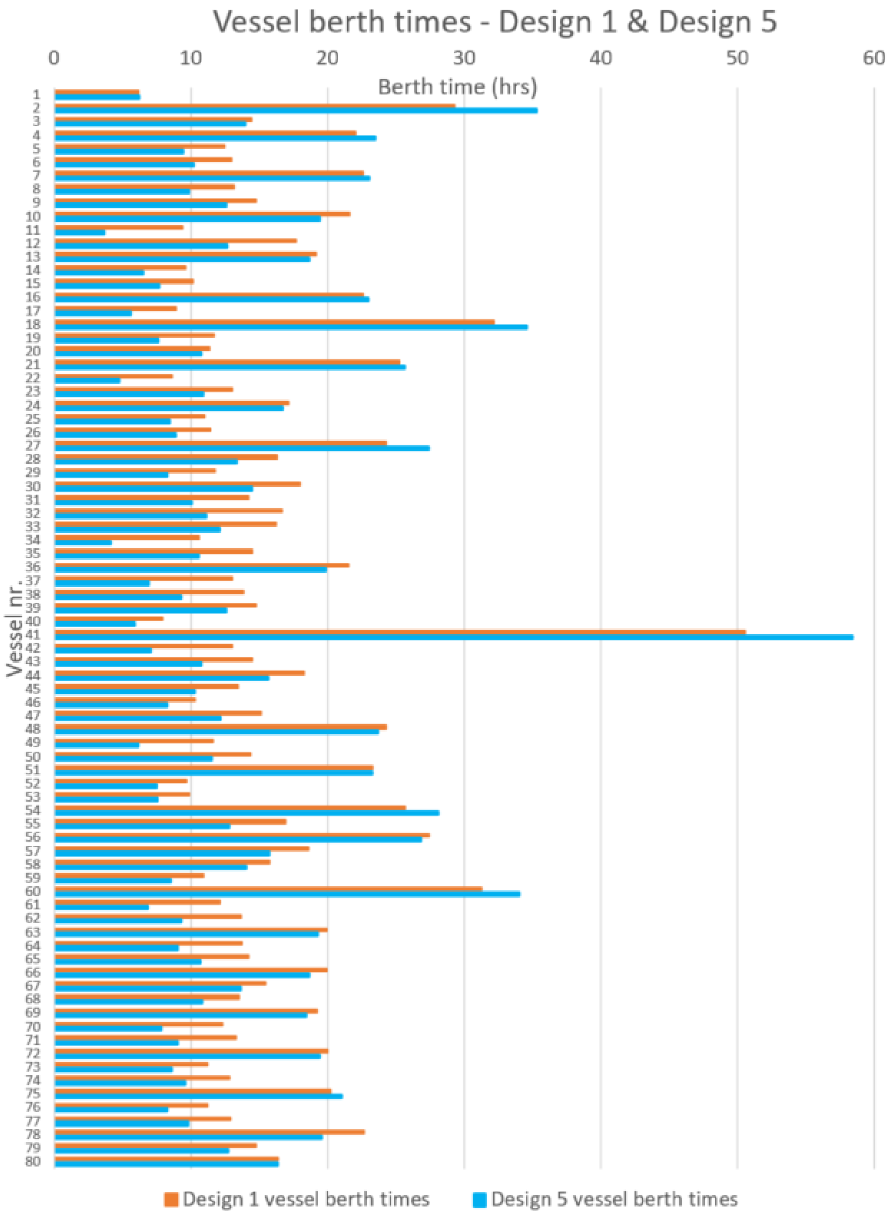

Figure 5.69: Vessels berth time comparison between Design 1 and 5. Orange bars represent Design 1's vessel berth times and blue ones Design 5.

Figure 5.70 displays the berth time for various scenarios under different TSB vehicle settings. Notably, the +5% and +10% demand scenarios exhibit nearly identical median berth times. However, upon closer examination of the average berth times, an increase is observed for higher demand scenarios. For instance, in the +5% demand scenario with 70 TSBs, the average berth time is 14.9 hours, whereas in the +10% demand scenario with the same number of TSBs, it increases to 15.6 hours. This discrepancy arises due to the previously mentioned effect of the system on small and large volume barges, resulting in both designs performing relatively similarly for small vessels and thus having similar berth times. Additionally, this difference is reflected in the net container handled per hour indicator, depicted in Appendix Figure A.52. Furthermore, it's observed that the road increase scenario slightly enhances the standard scenario. This improvement can be attributed to the better balance of volume between AGV and TSB operations, combining the working time percentage improvement of the quay cranes brought by AGVs with the enhanced loading efficiency of TSBs' double cycling operations.

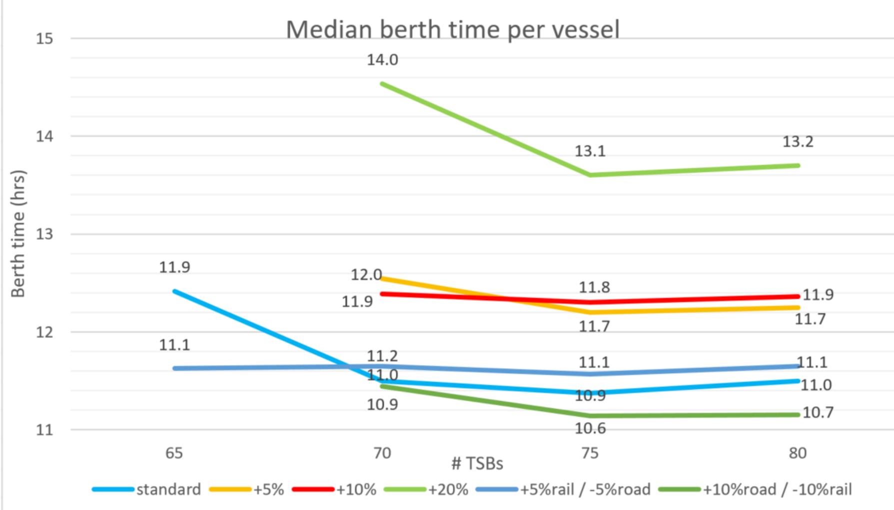

Figure 5.70: Median vessels berth times graph per scenario and number of TSB vehicles used. Unit: Hours.

Figure 5.71 compares the median berth times of demand scenarios between Design 5 and the base design (D1). Notably, Design 1 exhibits exponential increases in berth times as demand rises, whereas Design 5 shows more linear increments, indicating less variation between scenarios. This disparity is attributed to TSB congestion, which escalates with higher demand and TSB vehicle numbers due to their operation on tracks. In contrast, AGVs' performance remains consistent as the model assumes their availability for (un)loading operations in the absence of TSBs at the berth.

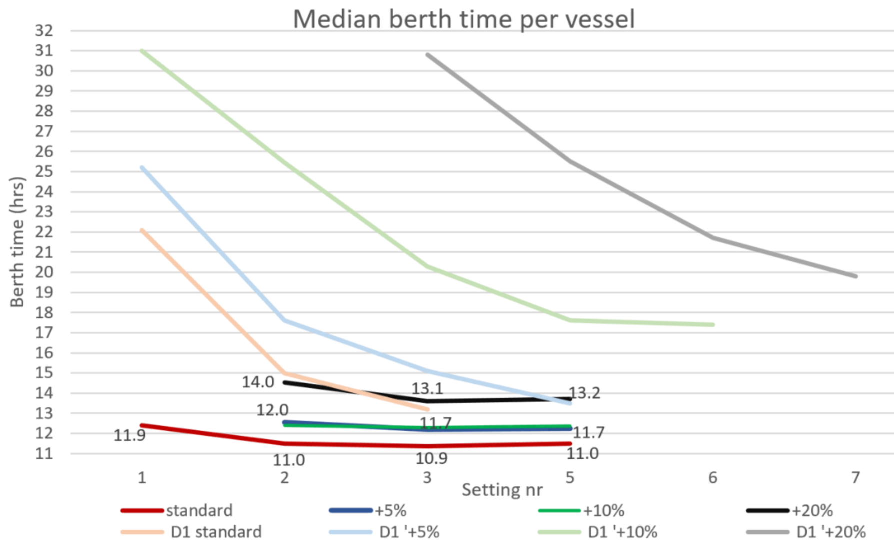

Figure 5.71: Median vessels berth times graph of demand scenarios and number of TSB vehicles used, comparing Design 1 (D1) and Design 5. Unit: Hours.

External terminals

Regarding external terminal volumes, Figure 5.72 compares Designs 1 and 5, showing again more differences than for the previous designs. Despite the lower number of vehicles in Design 5, Terminal 1 containers are handled faster, resulting in more vehicles arriving at external terminals. However, overall, the total average volume for Design 5 is slightly higher, showing a 6% increase.

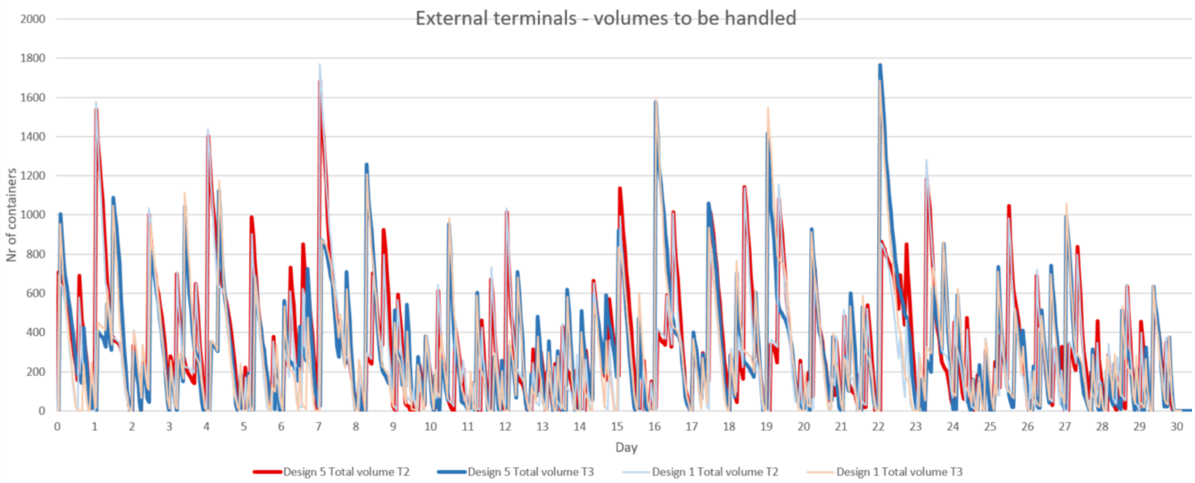

Figure 5.72: External terminals (T2 and T3) volumes to be handled per hour. Comparison for Design 1 and Design 5.

All terminals

Looking at volumes for all three terminals in Figure 5.73, the negative slope indicates efficient and distributed handling. TSB volumes for Terminal 1, Terminal 2, and Terminal 3 are quite similar, with Terminal 1 volumes slightly lower. The graph shows again how the TSB containers to be handled for T1 is very low compared to the total T1 containers (AGV + TSB), as previously explained. In Appendix Figure A.53, the average volume per terminal is illustrated for each scenario. It demonstrates a similar balance between terminal loads as depicted in this figure, particularly for successful scenarios.

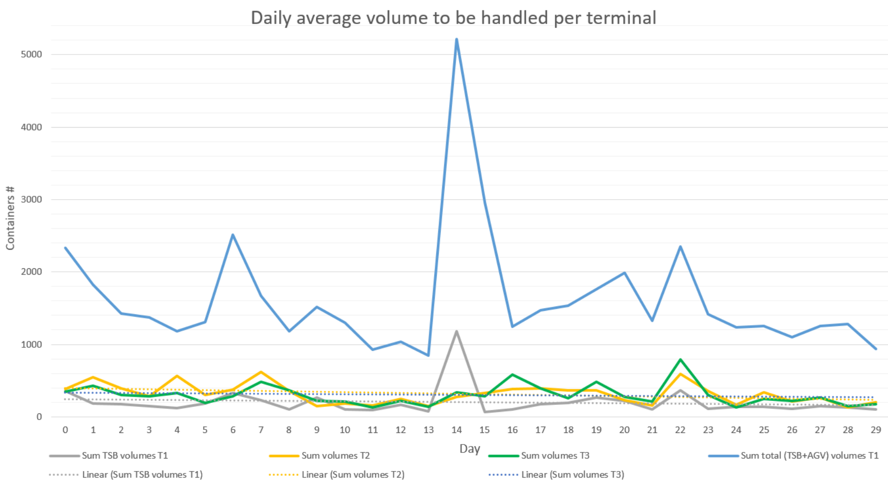

Figure 5.73: Daily average volume per hour per terminal and their trend-lines in dotted lines. Volumes for terminal 1 containers are plotted twice: for only TSB containers, and for the total (AGV + TSB) volumes.

Figure 5.74 illustrates the average total container volume per day for the primary TSB settings of each scenario. These volumes demonstrate consistent performance, with no noticeable buildup over time. Similarly, the daily average volume graphs for the remaining scenarios can be found in Appendix A.1.5, as well as further insights into the slope index and end time per scenario, with slope indicators over the limit align with scenarios where imbalances are evident.

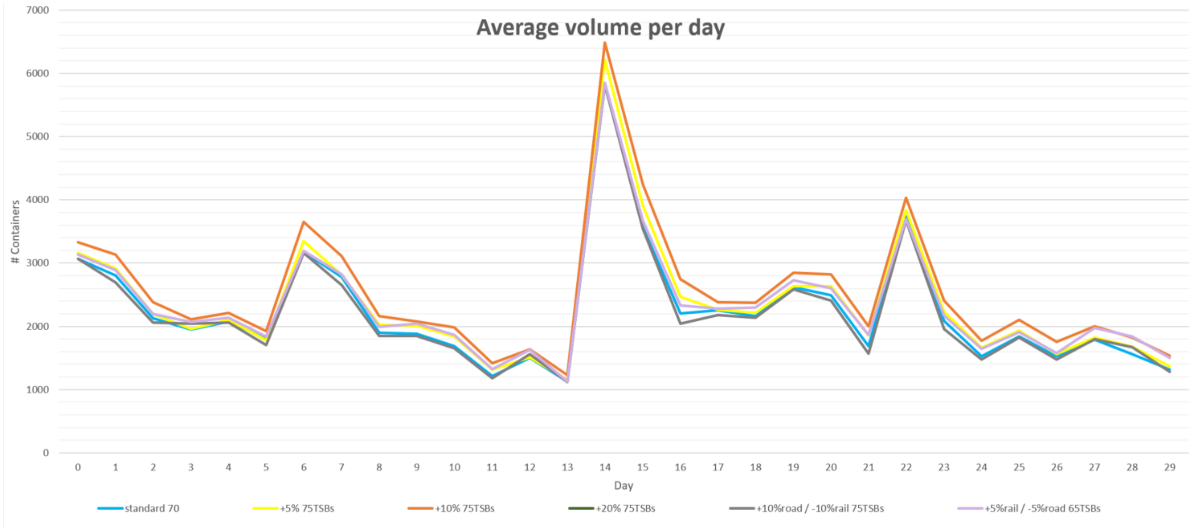

Figure 5.74: Design 5 main vehicle settings of each scenario. Daily average hourly total volume to be handled.

TSB vehicles

The TSB vehicles' key performance indicators (KPIs) are detailed in Table 5.75. A new metric, 'stopped system (empty) time', is introduced in this design, representing the duration TSB vehicles remain idle due to the absence of containers to handle. This phenomenon was absent in previous designs where containers were consistently available for handling. In Design 5, however, TSB containers are prioritized initially, leaving some instances where TSBs are idle while AGV operations are ongoing. On average, this idle time amounts to approximately 2% of the total operational time per vehicle, translating to around half an hour per day per vehicle. This downtime could potentially be utilized for maintenance or other operational activities.

Furthermore, the pure waiting time for TSB vehicles is notably reduced to 15%, nearly half of that observed in the first design (31%). This reduction can be attributed to the congestion primarily stemming from loading operations at Terminal 1. As Terminal 2 and Terminal 3 are treated as black boxes, the majority of congestion occurs at Terminal 1. With fewer TSB containers being handled at Terminal 1 in Design 5, the waiting and congestion time for TSB vehicles are significantly diminished.

Table 5.76 outlines the TSB vehicles' waiting/stopped time percentage for the different scenarios, demonstrating how increasing vehicle numbers may not yield significant benefits and can lead to increased congestion. Despite similar increments across scenarios as TSB vehicle numbers increase, the rail increase scenario exhibits the lowest waiting times. This is attributed to a higher volume allocation to AGVs, enabling faster and more efficient TSB volume service and resulting in a higher share of 'stopped system' time, during which vehicles remain idle until new volumes arrive for handling.

Nr TSB vehicles	70
Average covered Distance / TSB (km)	51398.7
% moving time	56%
% waiting/stopped time	15%
% Stopped system (empty) time	2%
% time at external terminals	27%
% time empty	10%
total modelled TSB moves	150027
total AGV moves	87902

Figure 5.75: TSB statistics for 70 vehicles. Distance in km.

Volume T1	65	70	75	80
standard	14%	15%	16%	18%
+5%		15%	16%	18%
+10%		15%	16%	18%
+10%		15%	17%	18%
+5%rail / -5%road	14%	15%	15%	16%
+10%road / -10%rail		16%	17%	18%

Figure 5.76: TSBs waiting time % for all scenario and number of TSBs. The color range ranks the scenarios outputs from best (green) to worse performer (red).

Cranes

Regarding resources, the productivity of quay cranes significantly increases in terms of working time percentage (88% vs. 57% for Design 1) due to the continuous availability of AGVs when TSBs are not at the berth. However, the net average container moves per hour per crane sees only a modest improvement, with an additional 3.9 containers per hour per crane, attributed to the lower efficiency of single-cycle operations.

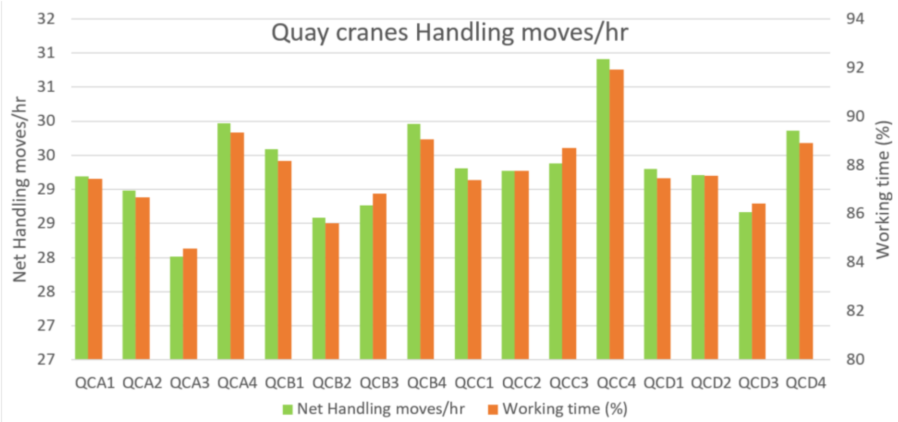

Figure 5.77: Quay cranes net productivity and net handling moves per hour.

5.7. Conclusion

To conclude this chapter, let's provide a brief summary comparison of the five different designs for their base scenarios' main settings, as depicted in the graphs below and summarized in Figure 5.78.

	Design 1	Design 2	Design 3	Design 4	Design 5
Nr of TSB vehicles used	90	90	95	90	70
Average berth time (hrs)	16.3	14.5	18.9	15.7	14.2
Median berth time (hrs)	14.5	12.6	17.0	13.5	11.0
Average containers handled / hr	101.9	115.0	88.2	105.8	117.2
Average net QC moves/hr	25.5	28.7	22.1	26.4	29.3
Average vol. T1 (# cntnrs.)	1687	1608	2044	1719	1628
Average vol External Terminals (T2 & T3) (# cntnrs.)	285	294	370	302	309
Average TSB ditance travelled (km)	44681	41749	39217	44615	51399
Average TSB waiting time %	29%	31%	28%	31%	15% (+ 2% stopped)

Figure 5.78: Summary comparison of main performance indicators for all designs main settings. For each indicator, the color range ranks the designs from best (green) to worse performer (red).

Examining Figures 5.79 and 5.80, Design 5 demonstrates the best performance in terms of median berth times, while Design 2 surpasses all others in terms of containers per hour handled. The positive performance of Design 5 is attributed to the combined use of AGVs and TSBs, albeit with certain relaxation assumptions, which will be elaborated upon in the Discussion chapter 6. Notably, Design 5, similar to Design 2, incorporates a shortcut track around the terminal, offering dual benefits. Additionally, the remaining designs follow the performance order from best to worst as follows: Shortcut design, extra switches, standard, and double track designs. The red line in the Figure denotes the reference benchmark of median berth time in Germany, 18.96 hours (source: UNCTAD, 2019), which all TSB settings for Designs 2, 4, and 5 outperform. However, Design 1 would require at least 90 vehicles, and Design 3, 95, to meet this benchmark.

Furthermore, Design 4 outperforms the standard design for smaller numbers of vehicles, but the base design outpaces Design 4 for 95 or more vehicles, as excessive vehicles at the berth render the extra switches counterproductive.

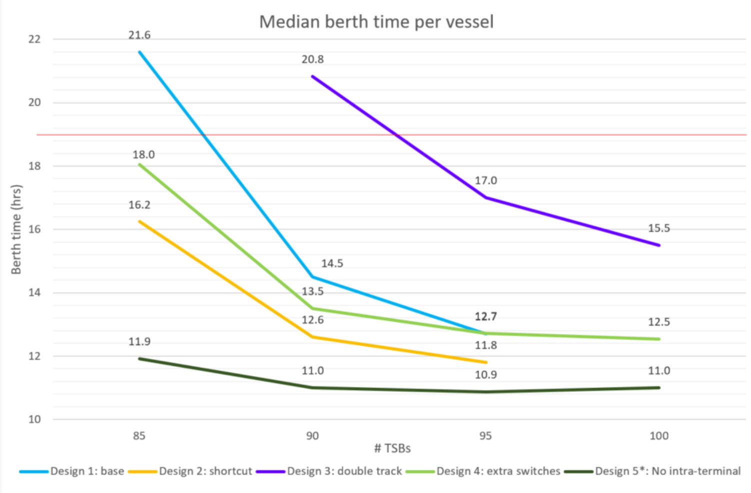

Figure 5.79: Median vessels berth times graph for all Designs base scenarios and number of TSB vehicles used. The red line marks the reference benchmark of median berth time in Germany: 18.96h. **Note that the X axis for Design 5 is different, and corresponds to: 65, 70, 75 and 80**. Unit: Hours.

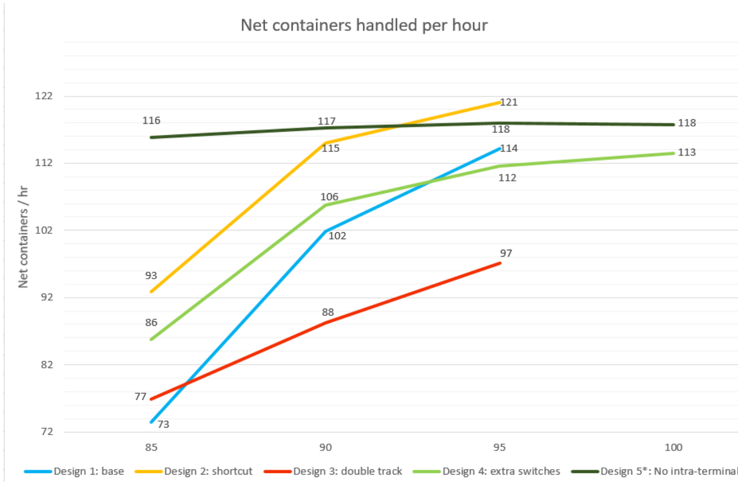

Figure 5.80: Net containers handled per hour per Design base scenario and number of TSB vehicles used. **Note that the X axis for Design 5 is different, and corresponds to: 65, 70, 75 and 80**. Net: Total containers/total berth time hours

Figures 5.81 and 5.82 show similar performance for all designs but Design 3, performing notably worse.

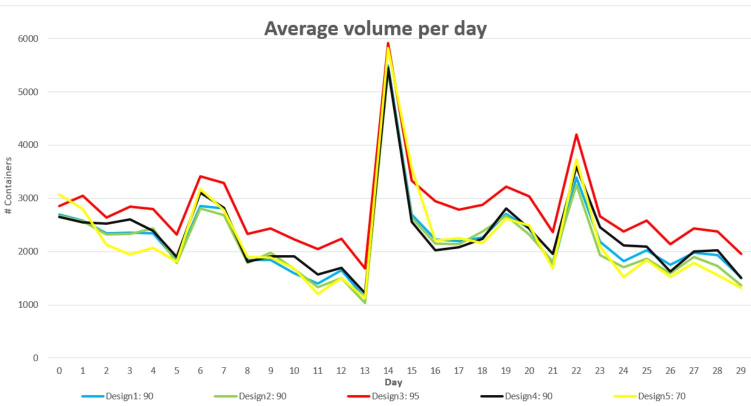

Figure 5.81: All designs main vehicle settings. Daily average hourly total volume to be handled.

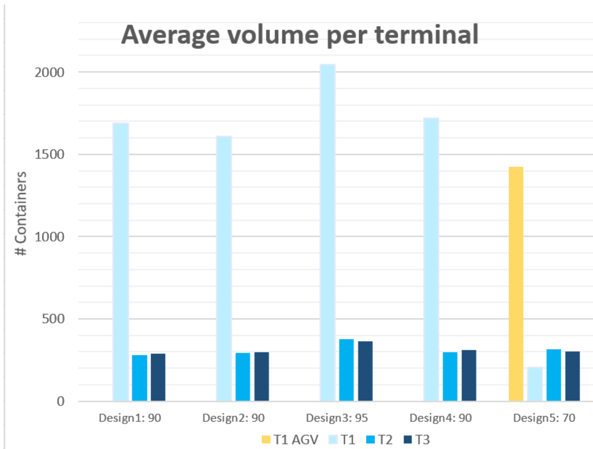

Figure 5.82: Each design's main TSB setting. Average volume to be handled per terminal.

Examining the usage of TSB vehicles in Figures 5.83, Design 5 emerges as the best-performing once again. This is attributed to its lower presence at Terminal 1, where the majority of waiting time/congestion arises, as external terminals are modeled as black boxes and do not contribute to waiting times. Generally, there exists a direct relationship between waiting times and berth time efficiency in the designs. However, the relation between Design 1 and Design 4 shows a slight deviation: when Design 4 performs better in berth times than Design 1, it also fares better in waiting times, and vice versa.

Regarding the distance covered, as illustrated in Figure 5.84, similarity is observed between Design 1 and Design 4, with Design 2 outperforming both. The distance traveled per TSB is naturally higher for Design 5 and lower for Design 3, corresponding to the lowest and highest number of vehicles in use, respectively.

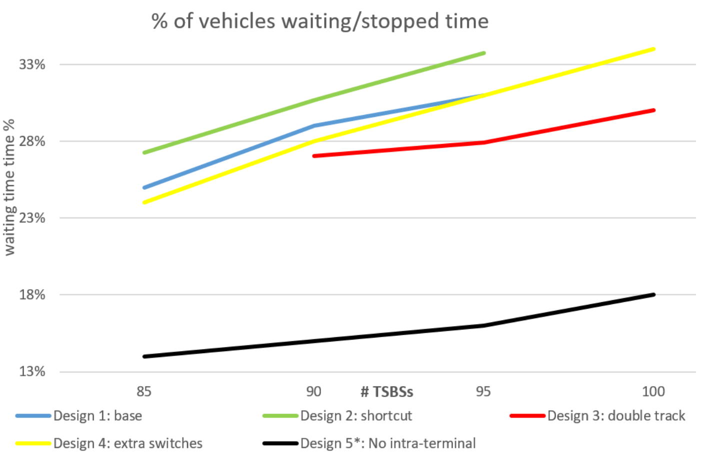

Figure 5.83: All designs main scenarios comparison. TSBs waiting time % per design and number of TSBs.**Note that the X axis for Design 5 is different, and corresponds to: 65, 70, 75 and 80**.

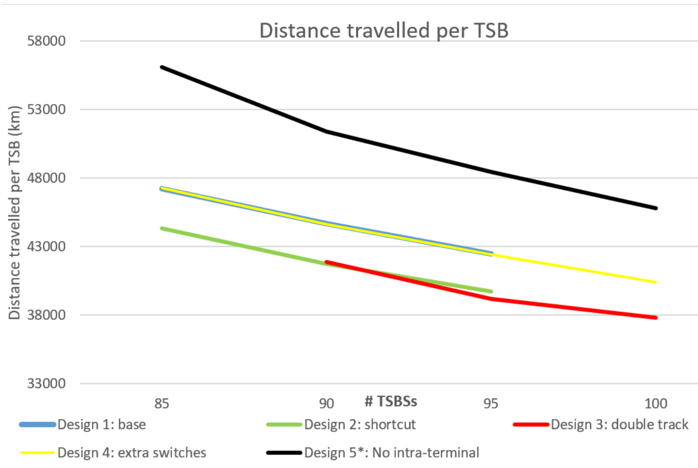

Figure 5.84: All designs. Distance (in km) covered per TSB over the whole period per TSB setting. **Note that the X axis for Design 5 is different, and corresponds to: 65, 70, 75 and 80**.

In summary, all designs, with the appropriate number of vehicles, have demonstrated an improvement in the berth time benchmark, which was prioritized due to its critical importance for terminal operators and the port overall. This has been proven for each design even with demand increases of up to 10% and with each of the tested modal share scenarios. For the +20% scenario, multiple designs achieved median berth times of around 20 hours, only slightly above the benchmark. Despite some system inefficiencies such as congestion, quay cranes have been shown to be the bottleneck in these designs. Thus, increasing the number of quay cranes per berth could enhance system performance, enabling it to handle increased demand volumes while meeting the benchmark goal.

Furthermore, the productivity of quay cranes in terms of container moves per hour, averaging above 25 moves/hr for most scenarios, falls within industry standards of 25-30 moves per hour (Navis, 2015). Additionally, the objective of balanced volume distribution across all terminals has been achieved, with stable volumes allocated to each terminal.

Further discussion on these results, the integration and impact of the system into port logistics will be presented in the subsequent Discussion chapter 6.

6
Discussion

6.1. Reflection on designs performance & limitations

6.1.1. Designs performances

The findings from the conclusion of the results chapter highlight Design 5 as demonstrating the most favorable performance with respect to median berth times. This is primarily attributed to the integrated utilization of AGVs and TSBs, albeit under certain relaxation assumptions. Firstly, it was assumed that the quay cranes possess the capability to discern, prior to container retrieval from the vessel, the destination of each container, thereby facilitating the selection of either a TSB or AGV container. However, it's worth noting that this functionality is not currently operational in existing crane systems, posing a significant implementation challenge for such a mixed transport system. Consequently, most of the design alternatives explored in this study opted for a TSB-exclusive approach. Secondly, the assumption that contributed to the success of Design 5 was that AGVs are always available at the berth, ready to facilitate vessel loading and unloading in the absence of a TSB. This assumption is premised on the hypothesis that, with a higher proportion of demand (road and ITT) being diverted to TSBs, the overall demand for AGVs would be reduced, thus enabling a better utilization of available resources for transshipment and rail container operations at the terminal. However, it is acknowledged that in practical implementation, factors such as congestion and operational inefficiencies may arise, leading to potential time wastage. It's important to note that this study primarily focused on TSB operations rather than AGVs, hence the modeling of AGVs did not incorporate such detailed accuracy. Nonetheless, the objective of Design 5 was to provide an initial exploration on how the mixing of these two transport modes could impact the operations, and how the system design would look like, which has been achieved.

Despite Design 5 demonstrating superior performance in median berth times, the overall productivity of Design 2, which is measured by net containers handled per hour or average berth time, surpasses that of Design 5, when using 95 or more vehicles. This discrepancy arises because while Design 5 results in shorter lead times for low-volume vessels, it yields longer lead times for high-volume vessels, thereby benefiting from the median indicator over the average one. Additionally, Design 2 exhibits the most favorable performance in terms of traveled distance per vehicle, attributed to the distance-saving effect facilitated by the addition of the shortcut track. This implies potential reductions in energy consumption and operational costs. Furthermore, Design 4, featuring extra tracks connecting the berth and fast track, also demonstrates improved performance compared to the base design. This suggests that combining elements from both Designs 2 and 4 could yield even greater benefits. It's worth noting that Design 4 may incur higher costs due to the added switches and short tracks, while Design 2 may also have increased costs owing to the additional 8.9km track compared to Design 1. In contrast to the other designs that exhibit improvements, Design 4 performs worse than Design 1 due to added congestion for external vehicles resulting from the removal of the fast track. To address this issue, an alternative design involving the addition of a third track acting as a fast track could be explored. While this design offers superior performance, it is expected to incur higher costs due to the increased number of switches and track length. However, one of the primary motivations for testing this configuration is the enhanced resilience it offers. With two tracks operating independently, any issues affecting one track would not disrupt the overall operations, albeit with potentially increased congestion on the operational track.

The performance of all the designs was predictably sensitive to demand volumes, with increased volumes leading to longer loading times for vessels and consequently higher berth times. However, despite increased demand (up to a 20% increase for T1), the system could still handle it, albeit resulting in increased congestion due to a higher number of vehicles at the terminal berths. This congestion primarily comes from getting to the quay cranes (QCs) bottleneck, as only a certain total productivity of containers per hour can be achieved with four QCs per berth space. To address this, potential solutions include increasing the number of cranes per berth space or adapting the number of cranes based on berth occupation and vessel size. Additionally, the system's sensitivity to demand modal share was evident, with higher rates of rail transport yielding better performance compared to road transport, owing to the proximity of rail storage to the berth, which reduces the average time per container move.

The design scenarios revealed clear trade-offs between the number of TSB vehicles and performance, however also increased waiting times of the vehicles, resulting in lower utilization rates. Despite improvements in performance, each design reached a maximum capacity constrained by the quay cranes, which became bottlenecks, slowing down the system. Additional trade-offs affecting the system include the location of the dry port, set at 20km in this research. Longer distances necessitate more vehicles, as they take longer to complete a round tour. However, the increase in vehicles needed for increased dry port distance is less than proportional, given the high proportion of vehicle movement occurring within the terminal. Moreover, increasing distances would mean a higher proportion of time spent in transit rather than waiting. Another noteworthy observation is the higher performance of berth space 1 compared to others, owing to its lower congestion resulting from proximity to the terminal entrance.

All in all, as discussed in the results chapter, all of the Designs, with the appropriate TSB vehicle settings, successfully meet the objectives of the system by handling the entire port container volumes and outperforming the berth time benchmark for Germany, which stands at 18.96 hours (source: UNCTAD, 2019).

6.1.2. Research limitations

The research is subject to limitations stemming from the assumptions made for the system modeling, do to the first stage of the research, on a totally new topic.

Firstly, the relaxation of constraints regarding the allocation of containers to quay cranes could impact the results. However, given the novelty of the research, not all constraints could be accounted for. Incorporating all constraints would necessitate further research involving a full optimization of the system, including coordination of container arrivals from the yard with those from the dry port to allocate containers in the correct order and position. This would align with the use of double cycling, the requirements of which should be integrated into this optimization process.

Additionally, another limitation of the model is the black box representation of external terminals. This raises two important discussions: the determination of buffer times and potential congestion at these terminals, and the need for balancing and prioritizing operations across all three terminals.

In this study it was assumed a perfect operation in the external terminals, without any congestion. Consequently, vehicles entering these ”black boxes” were assigned buffer times based on the probability of completing a certain number of trips around the terminal for loading and unloading rail and transshipment containers, without considering congestion. However, in reality, fully modeling these terminals would likely reveal congestion, leading to increased time spent at these external terminals. While the volume could still be handled, similar to Terminal 1, it would likely require a higher number of TSB vehicles and a more balanced allocation of resources across all three terminals. By increasing the number of vehicles and redistributing congestion across the terminals, the overall performance could be maintained without encountering bottlenecks in the early TSB setting, as congestion would be spread across all three terminals rather than concentrated at Terminal 1.

The other discussion topic related related to not modelling T2 and T3 is the balancing of loads across the terminals. In this study, since T2 and T3 were not modeled and do not have specific berth time KPIs, the primary goal is to keep their volume low and manageable, ensuring timely handling without buildups. Conversely, the focus for Terminal 1 (T1) is on minimizing berth times. As a result, there is a prioritization of T1 over T2 and T3 when selecting which export containers to send from the Dry Port. T2 and T3 essentially receive whatever volume remains after T1 has been served by its maximum set number of vehicles. While in this research T2 and T3 are being served successfully, when modelling them, their berth times will also need to be minimized, finding a possible confrontation between the three terminal priorities. The implications of this issue in real-life scenarios are further discussed in the next section.

Overall, optimization is crucial for addressing the current model limitations and improving overall system performance. By optimizing the assignment of containers and coordinating their movement from the yard and dry port, considering their Quay Crane (QC) destination, congestion at the port can be minimized. This optimization process will ensure more efficient operations and enhance the effectiveness of the entire logistics system.

6.2. Impact of maglev on port logistics

During the research process, in addition to discussions with experts from the TSB department, two meetings were held with representatives from the Hamburg Port Authority (HPA) and the port simulation consultancy Portwise. In this meetings the research was discussed, with special focus on the simulation model and the assumptions, as part of the model validation. These assumptions have already been treated in the previous section of the discussion. In addition to that, discussion was held on the suitability of the TSB system in real-life port operations. One of the main challenges identified was the direct connection of the system to the berth, which deviates from the current 'status quo' of port operations where berth transport is typically facilitated by AGVs, yard trucks, or other modes from the yard. The transport modes used until the date to connect the dry port to the terminal, primarily utilizing the railway system, required container's intermediate storage. While cost-efficient, the railway lacks the flexibility and reliability of the TSB system, as it requires consolidation of containers into rail cars before transportation, leading to unpredictability. Moreover, a direct connection to the berth would necessitate extensive planning and coordination to consolidate and transport containers individually stored across multiple storage blocks at the dry port. Additionally, railway transport generates high peaks and congestion upon arrival at the berth, requiring intermediary modes for unloading and container placement. In contrast, the TSB system offers an adaptive infrastructure, allowing for closer turns and interaction with terminal cranes and AGVs. Additionally, railcars do not provide as fast transportation as TSBs. In this design, TSBs can reach the terminals in about 8 minutes, which is comparable to AGVs, allowing the system to have nearly the same flexibility and responsiveness. These technical characteristics challenge the existing need for intermediate storage and suggest the feasibility of a direct connection to the berth. Thus, the research aimed to explore how the TSB system could be feasible to perform in this setting and overcome this challenge.

Considering the comparison between trucks and maglev for the connection between the dry port and seaport terminals, it becomes evident that utilizing trucks is not a viable alternative within the proposed setting. With the entire share of road containers stored at the dry port (30.8% of total demand in this study), the requirement for a substantial number of trips would pose high logistical challenges. Shippers would face significant hurdles in organizing additional transportation, in addition to unnecessary costs; while in case of terminals arranging such services would also incur high operational expenses. Furthermore, coordinating trucks for just-in-time transportation to and from the berth would be highly complex due to their unpredictable behavior, with variability in travel times, potential congestion issues and increased risk of human error, among others. Consequently, the feasibility of establishing a direct berth connection using trucks seems unattainable, necessitating intermediate storage similar to the rail system. Overall, relying on trucks for this service would fail to address the initially identified issues, resulting in increased emissions, continued congestion, and insufficient increase in terminals' capacities due to the persistent need for intermediate storage. Consequently, trucks are deemed an unsuitable alternative for this scenario.

Demonstrating the feasibility of the integration of the maglev system (TSB) and showcasing its superior performance compared to the previous system, opens up a new paradigm. This sets the stage for a fully integrated port system, where different terminals are interconnected and overall capacity is increased due to the 'terminals' extension' at the dry port.

A well-implemented maglev system, as proposed, offers advantages for all stakeholders involved. The port authority gains the ability to connect terminals for more efficient inter-terminal transport (ITT), while addressing the issue of congestion caused by truck traffic around the port infrastructure, and promoting a more sustainable mode of transportation. ITT via maglev fosters a more interconnected and cooperative port environment, enhancing the port's role as a transshipment hub and improving connections with barge, rail, and road modes of transport. Terminal operators benefit from expanded storage capacities, enabling them to focus on increasing rail transport shares, while reducing the number of container moves required within the terminal. Additionally, they can offer vessel carriers shorter berth times. Barge operators can streamline their operations by focusing on a single terminal for loading and unloading containers, leading to increased efficiency and better volume control. The expanded storage capacities may allow terminals to extend container drop-off and pickup time windows, providing more flexibility for shippers and freight forwarders. Truckers benefit from improved access to the terminal via the dry port, avoiding congestion and reducing waiting times, thus enhancing predictability in their processes. Finally, the local community enjoys the benefits of reduced congestion and pollution (including noise pollution) around the port infrastructure, as the dry port is situated on the outskirts of the city.

As discussed in the previous section, one of the challenges in integrating this project is coordinating multiple terminals, each with its own interests. The entity operating the system would need to balance the priorities of all terminals. A potential solution could be a centralized model predictive control (MPC) approach, where terminals collaborate by sharing vessel schedules, priorities, and real-time data on resources and vessel status. This centralized coordination could help optimize operations across all terminals and enhance overall system efficiency.

To fully implement this system, the port would need to undergo several implementation stages due to its scale and complexity. Initially, a small-scale phase could involve creating the track between terminals and using the TSB solely for inter-terminal transportation, possibly including a barge terminal. Subsequently, the connection to the dry port could be established, with a partial shift of road storage to the dry port while retaining some at the seaport terminals. This phase would resemble Design 5, combining AGV transportation for yard storage containers and TSB for dry port and inland terminal transport. For this to work, QCs would need the capability to distinguish container's transport mode destinations. Over time, all road storage could transition to the dry port, enabling seaport terminals to focus entirely on transshipment and rail containers (Design 5). Then, the TSB could be integrated for intra-terminal transportation within the yard, operating as in the presented models. This final step would necessitate significant terminal restructuring to accommodate parallel storage blocks. The system's scalability could be enhanced by adding parallel tracks at the dry port and increasing the number of TSB vehicles. Furthermore, the maglev system offers flexibility in demand volumes, routing, and scheduling, enabling dynamic adjustments to changing operational requirements. Additionally, if QCs could identify each container's destination through various technologies, as mentioned, the system could reach even a higher flexibility by adding AGVs at the terminal to support the loading process, particularly during demand peaks or TSB system disruptions.

While the costs were not explicitly addressed in this research due to the novelty of the technology and the focus on technical design and operational performance, cost-related factors were still considered, as the track length, number of vehicles, number of cranes or amount of switches. Projects of this magnitude are long-term investments, typically involving both public and private funding over the long term. Various costing models could be explored, incorporating different terminals and shippers, to address operating costs and finance the system.

7 Conclusions, recommendations & future research

In conclusion, this research aimed to address the main research question: "How can a maglev transport system be integrated into seaport logistics, connecting it to a dry port, and how would the integration impact port operations?". Through the study, it was demonstrated that the integration of maglev technology, specifically the Transport System Bögl (TSB), offers significant potential to revolutionize port logistics, with a seamless connection between the dry port and seaport terminals, and improve operational efficiency.

The research explored various design scenarios aimed at integrating the TSB system into port operations, with a primary focus on connecting a dry port terminal to seaport terminals, with a direct connection to the berth, using maglev technology. Five distinct design configurations were developed and assessed through simulation modeling. Overall, the findings suggest that the integration of the TSB system offers a feasible solution to the challenges faced by traditional port logistics, such as storage capacity limitations and congestion in port access, while showing an improved berth time performance. By providing a direct connection to the berth from the dry port, the TSB system has the potential to streamline operations, increase efficiency, and reduce environmental impact, opening up a new paradigm for port logistics.

Based on the findings, it is recommended to Max Bögl to continue with a close collaboration with port authorities, conducting simulation case studies tailored to specific port parameters, requirements, objectives, and data, serving as proof of performance for potential integration projects. Moreover, working close with the port terminals, a comprehensive cost analysis of the project should be conducted, encompassing all potential expenses associated with system implementation, as could be the AGVs' sunk costs, restructuring of the seaport terminals, or construction of the dry port, among many others. Additionally, the company should explore collaboration opportunities with smaller scale ports facing space availability issues, particularly ports encircled by cities, and focus on ports encountering capacity limits or seeking expansion, while also addressing port road access problems and seeking a more sustainable mode of transport to reduce city pollution. Suitable examples include Genoa, Las Palmas de Gran Canarias, La Spezia, and Dublin ports. Initiation of small-scale pilot projects in ports, starting with lower volume links like ITT, is recommended; with a long-term goal of TSB utilization for connecting the port and dry port, which is where the system can really exploit its characteristics, and where it can be disruptive for the industry. Further research is needed on robust information systems, optimization algorithms, financing models, and pricing strategies, including methods to incorporate stakeholders' priorities and demands, thus facilitating collaboration and data sharing among terminals.

In terms of further research, due to the novelty of the study, some of the research recommendations align with those for Max Bögl, as they own the technology and are driving its development forward. Moving forward, expanding the model should remain a priority, with a continued focus on establishing a direct connection to the berth from the dry port to accommodate new export container loading requirements and include all terminals. This expansion would allow for the study of new algorithms that balance the volumes of all three terminals. Additionally, exploring optimization models to balance terminal requests and priorities while enhancing system efficiency, potentially using a centralized model predictive control (MPC) approach similar to the one proposed by Larsen et al., 2021, would be beneficial. Furthermore, conducting further research on the different pricing models applicable to these systems, considering factors such as volume and priority, and assessing the resulting impact, would provide valuable insights for future implementation. Additionally, it is important to acknowledge that the designs investigated in this research represent a subset of potential options, however there are more possible designs that could be explored in future research.

In conclusion, the integration of maglev technology into port logistics represents a promising opportunity to transform traditional port operations and meet the evolving demands of global trade. By embracing innovation and collaboration, stakeholders can harness the full potential of maglev systems to create more efficient, sustainable, and resilient port environments.

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A

Appendix

A.1. Results Appendix

A.1.1. Design 1: Base design

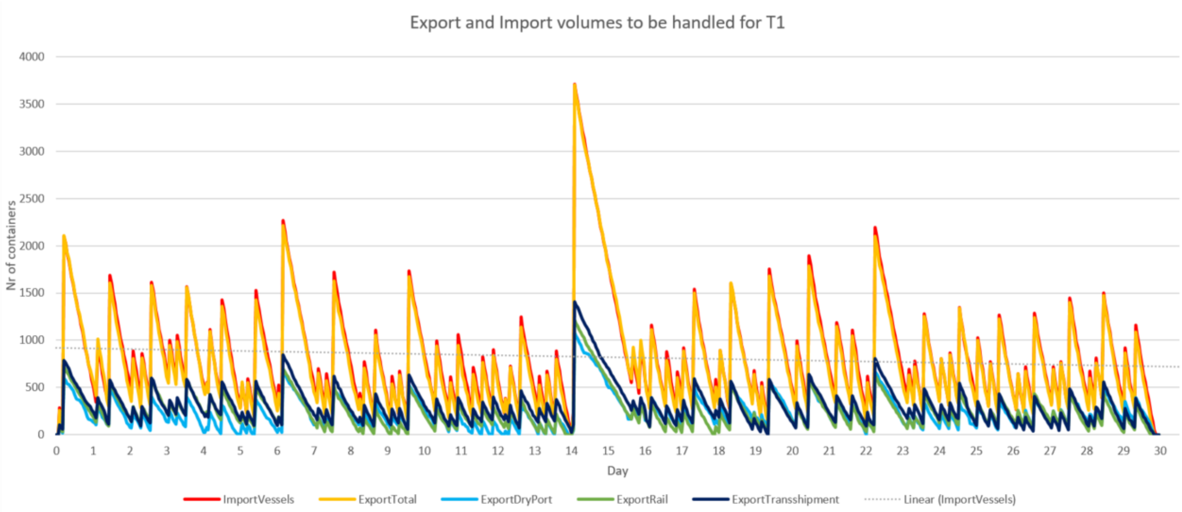

Figure A.1: Import and export volumes to be handled for T1, with the export being divided in its three different storage locations: dry port, transshipment and rail. As the container is handled the volume decreases, therefore low levels are preferred.

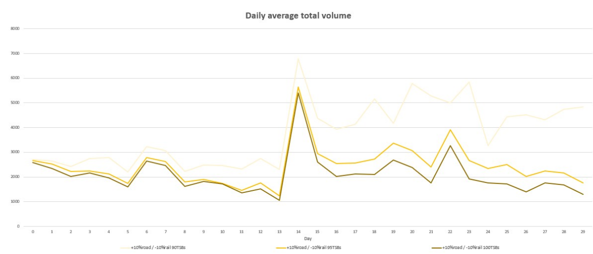

Figure A.2: Daily average hourly total volume to be handled for scenario +10% road / -10% rail.

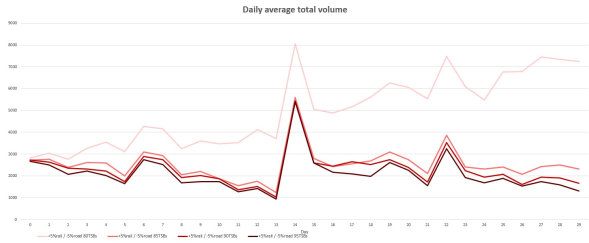

Figure A.3: Daily average hourly total volume to be handled for scenario +5% rail / -5% road.

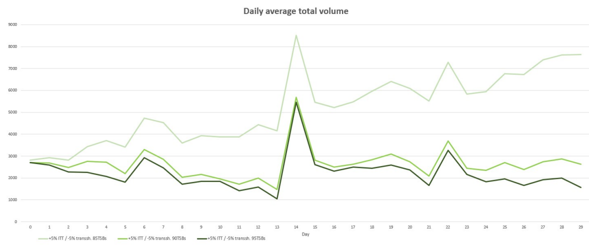

Figure A.4: Daily average hourly total volume to be handled for scenario +5% ITT / -5% transshipment.

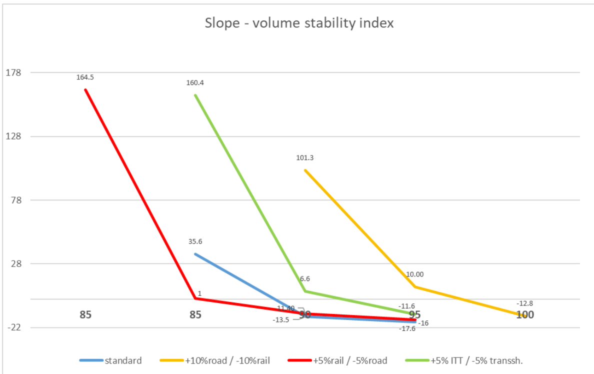

Figure A.5: The slope index shows the stability of the demand, and spots if there is a storage buildup.

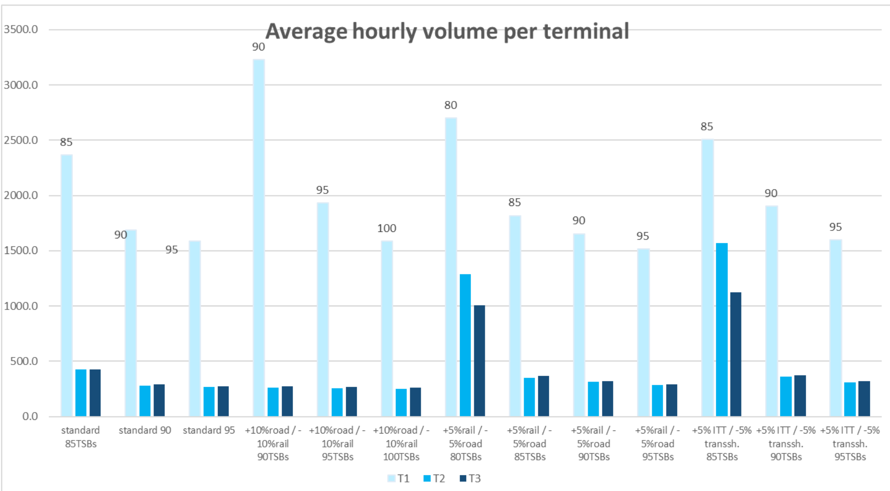

Figure A.6: Average volume to be handled per terminal.

A.1.2. Design 2: Double-loop around terminal

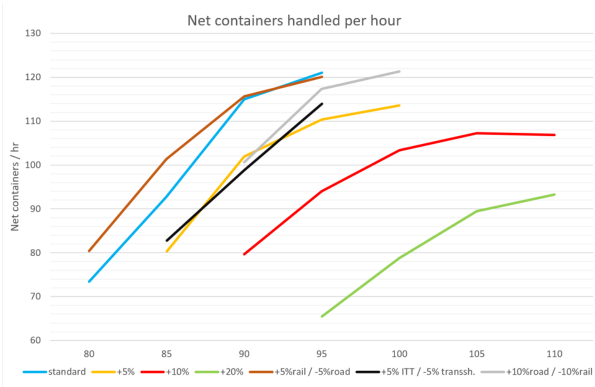

Figure A.7: Net containers handled per hour per scenario and number of TSB vehicles used. Net: Total containers/total berth time hours

Volume T1	80	85	90	95	100	105	110
standard	32.2	30.3	29.9	29.9			
+5%		30.8	30.3	30.1	30.0		
+10%			30.5	30.0	30.0	30.0	30.0
+20%				31.1	30.8	30.2	30.2
+5%rail / -5%road	31.0	30.3	29.9	29.9			
+5% ITT / -5% transsh.		31.6	30.1	29.9			
+10%road / -10%rail			30.1	29.9	29.9		

Figure A.8: Design 2 both scenarios data. Schedule end time per scenario. Red cells represents scenarios in which the end time surpassed the maximum expected time (30.6), in which the vessels schedule starts to have a delay, meaning the system setup is not feasible to handle the scenario demand. Unit: Hours.

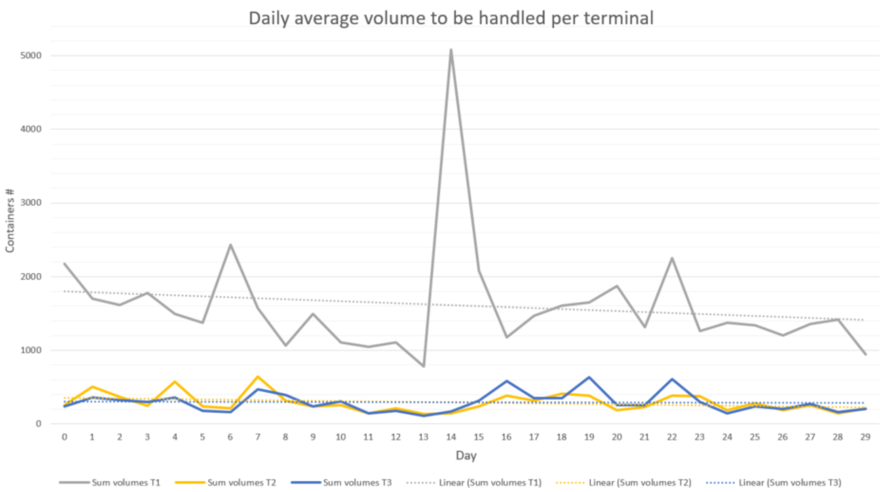

Figure A.9: Daily average volume per hour per terminal and their trend-lines in dotted lines

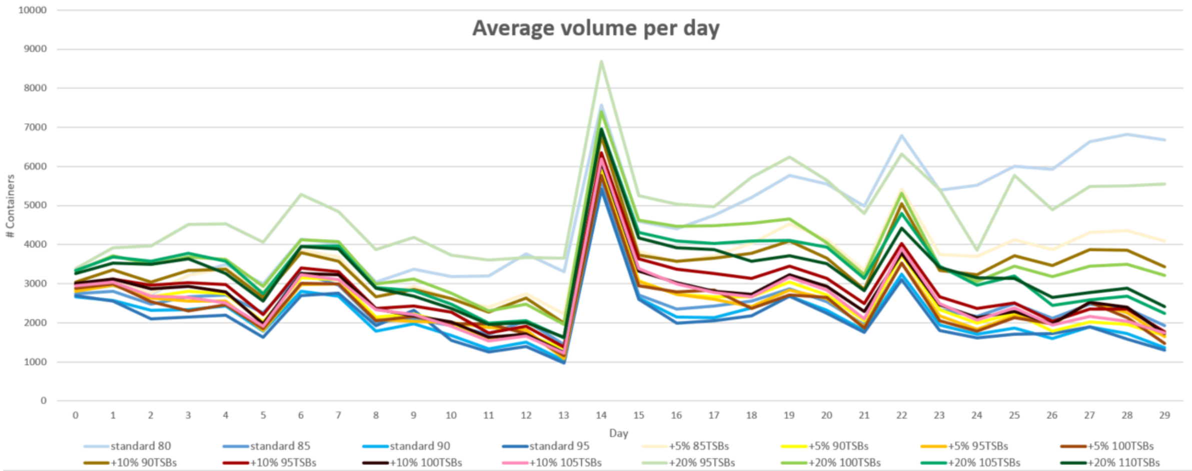

Figure A.10: Design 2 All Demand scenarios. Daily average hourly total volume to be handled.

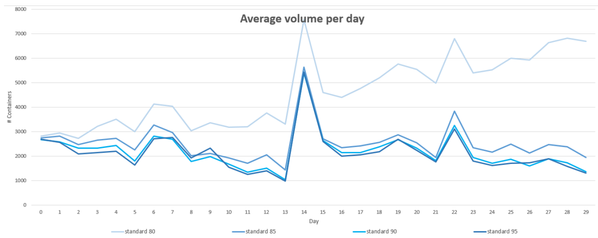

Figure A.11: Daily average hourly total volume to be handled for Design 2, standard demand of T1.

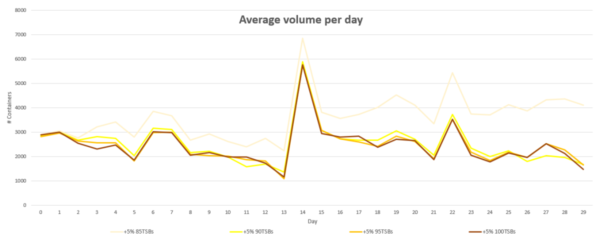

Figure A.12: Daily average hourly total volume to be handled for Design 2, +5% demand of T1.

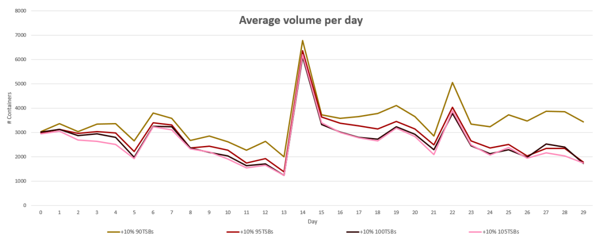

Figure A.13: Daily average hourly total volume to be handled for Design 2, +10% demand of T1.

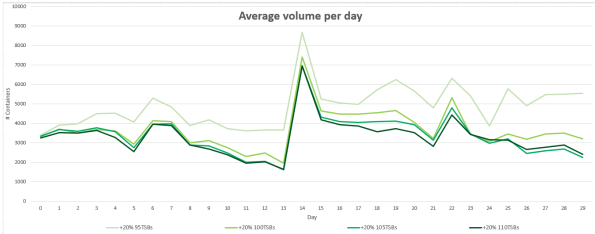

Figure A.14: Daily average hourly total volume to be handled for Design 2, +20% demand of T1.

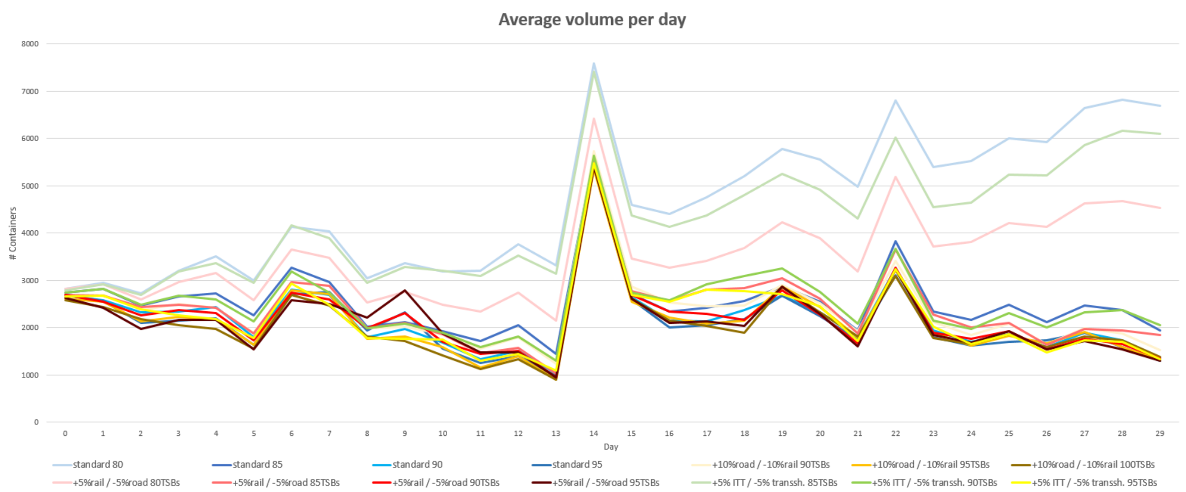

Figure A.15: Design 2 All Modal share scenarios. Daily average hourly total volume to be handled.

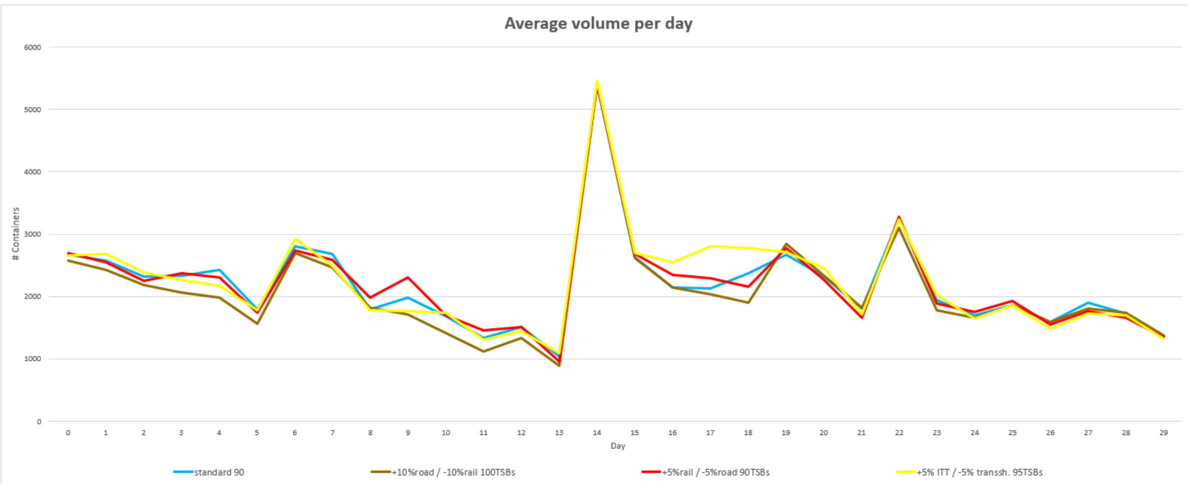

Figure A.16: Design 2 main vehicle settings of modal share scenarios. Daily average hourly total volume to be handled.

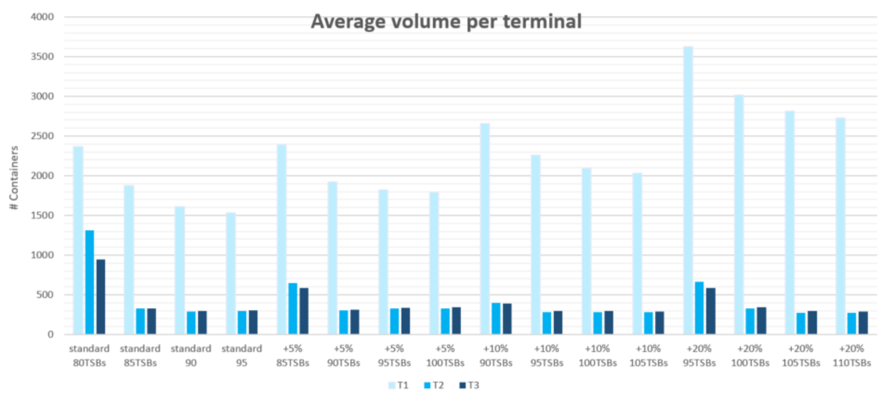

Figure A.17: Design 2 demand scenarios. Average volume to be handled per terminal.

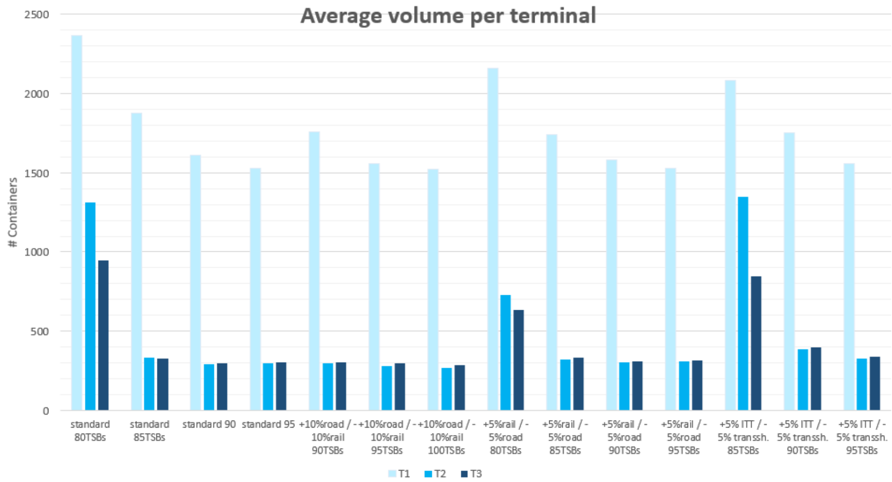

Figure A.18: Design 2 modal share scenarios. Average volume to be handled per terminal.

Volume T1	80	85	90	95	100	105	110
standard	140.7	-8.3	-18.7	-18.9			
+5%		52.8	-20.0	-13.7	-15.3		
+10%			27.6	-14.0	-14.9	-13.4	
+20%				60.4	10.0	-12.1	-6.5
+5%rail / -5%road	66.1	-10.7	-20.1	-18.4			
+5% ITT / -5% transsh.		109.0	-5.9	-17.6			
+10%road / -10%rail			-16.3	-15.0	-11.3		

Figure A.19: Design 2 demand and modal share scenarios slope index. The slope index shows the stability of the demand, and spots if there is a storage buildup.

Volume T1	80	85	90	95	100
standard	47306.7	44355.9	41749.5	39745.3	
+5%rail / -5%road	44895.1	42682.8	39892.2	37954.6	
+5% ITT / -5% transsh.		45622.9	42745.1	40608.2	
+10%road / -10%rail			45186.9	43074.6	41262.0

Figure A.20: Design 2. Distance (in km) covered per TSB over the whole period. The color range ranks the scenarios outputs from best (green) to worse performer (red).

A.1.3. Design 3: Double track

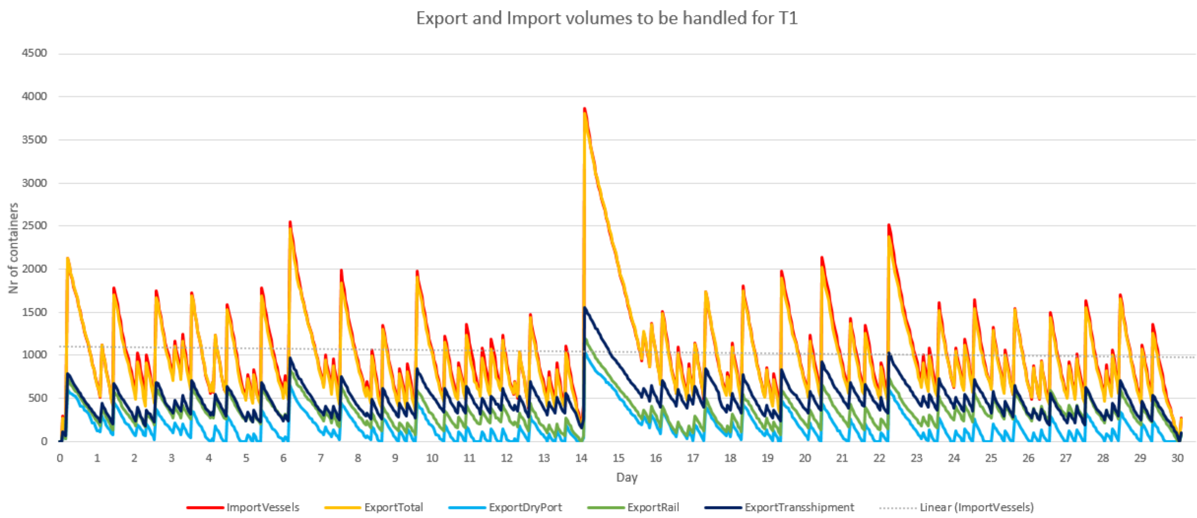

Figure A.21: Design 3. Import and export volumes to be handled for T1, with the export being divided in its three different storage locations: dry port, transshipment and rail. As the container is handled the volume decreases, therefore low levels are preferred.

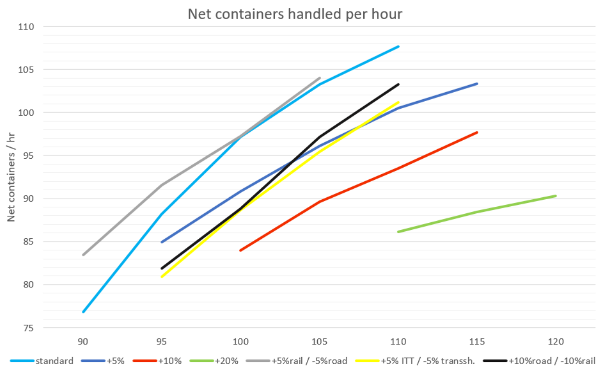

Figure A.22: Design 3. Net containers handled per hour per scenario and number of TSB vehicles used. Net: Total containers/total berth time hours

Volume T1	90	95	100	105	110	115	120
standard	31.2	31.0	30.0	30.0	30.0		
+5%		31.0	30.3	30.2	30.2	30.0	
+10%			30.3	30.2	30.1	30.0	
+20%					30.4	30.4	30.3
+5%rail / -5%road	31.1	30.3	30.2	30.0			
+5% ITT / -5% transsh.		31.6	30.2	30.0	30.0		
+10%road / -10%rail		31.4	30.1	30.0	30.0		

Figure A.23: Design 3 both scenarios data. Schedule end time per scenario. Red cells represents scenarios in which the end time surpassed the maximum expected time (30.6), in which the vessels schedule starts to have a delay, meaning the system setup is not feasible to handle the scenario demand. Unit: Hours.

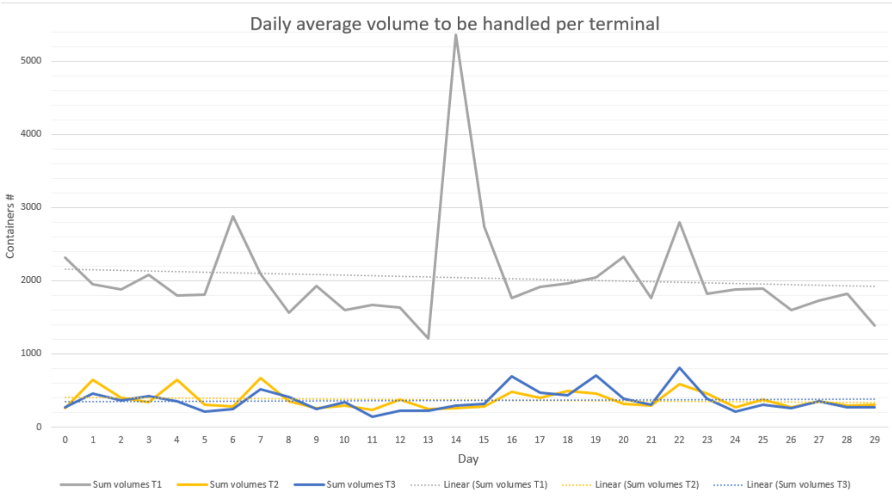

Figure A.24: Design 3. Daily average volume per hour per terminal and their trend-lines in dotted lines

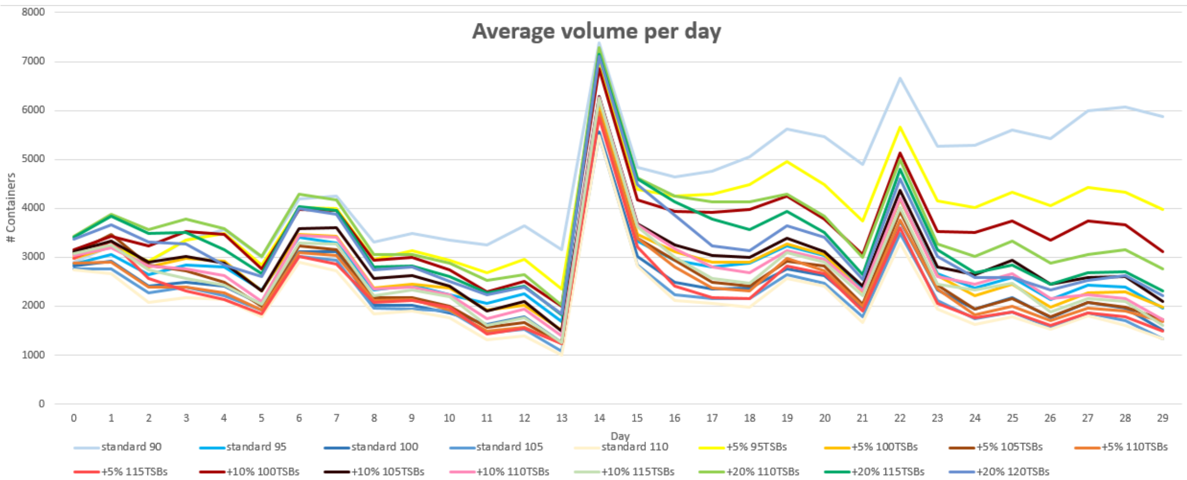

Figure A.25: Design 3 All Demand scenarios. Daily average hourly total volume to be handled.

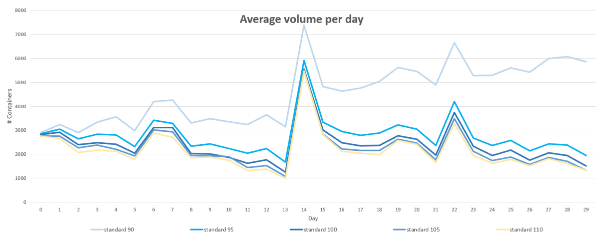

Figure A.26: Daily average hourly total volume to be handled for Design 3, standard demand of T1.

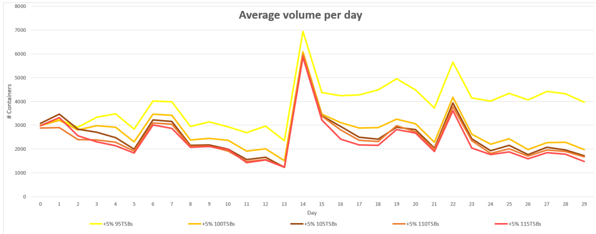

Figure A.27: Daily average hourly total volume to be handled for Design 3, +5% demand of T1.

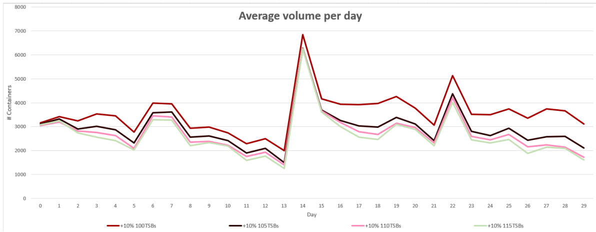

Figure A.28: Daily average hourly total volume to be handled for Design 3, +10% demand of T1.

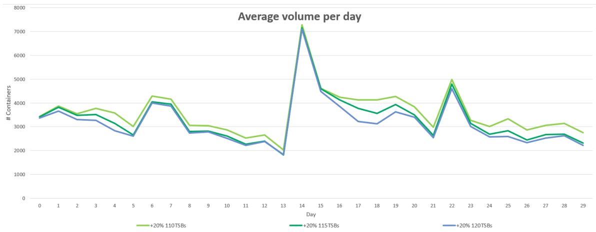

Figure A.29: Daily average hourly total volume to be handled for Design 3, +20% demand of T1.

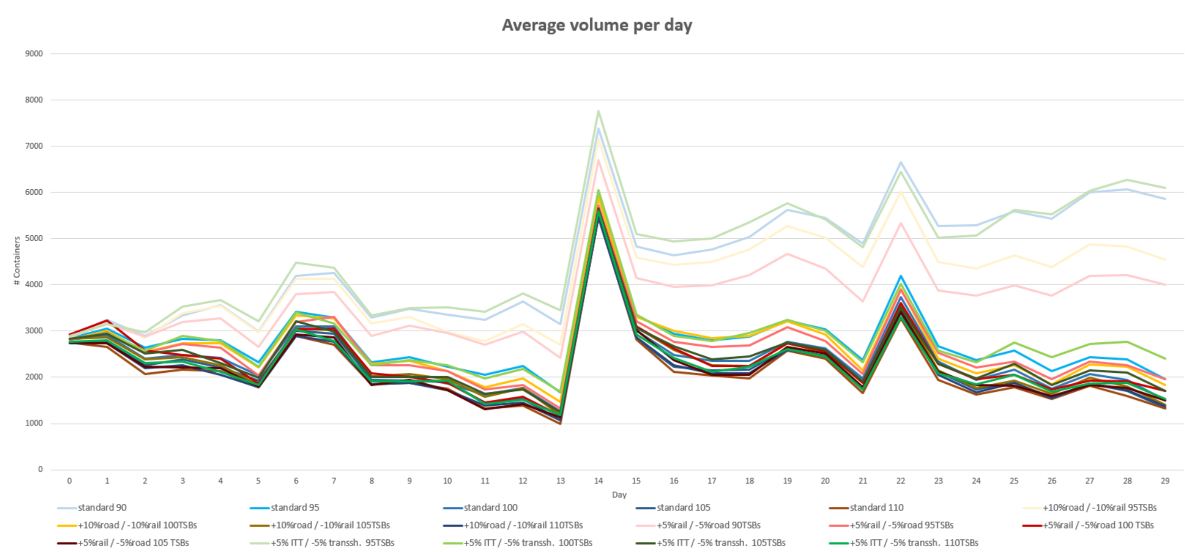

Figure A.30: Design 3 All Modal share scenarios. Daily average hourly total volume to be handled.

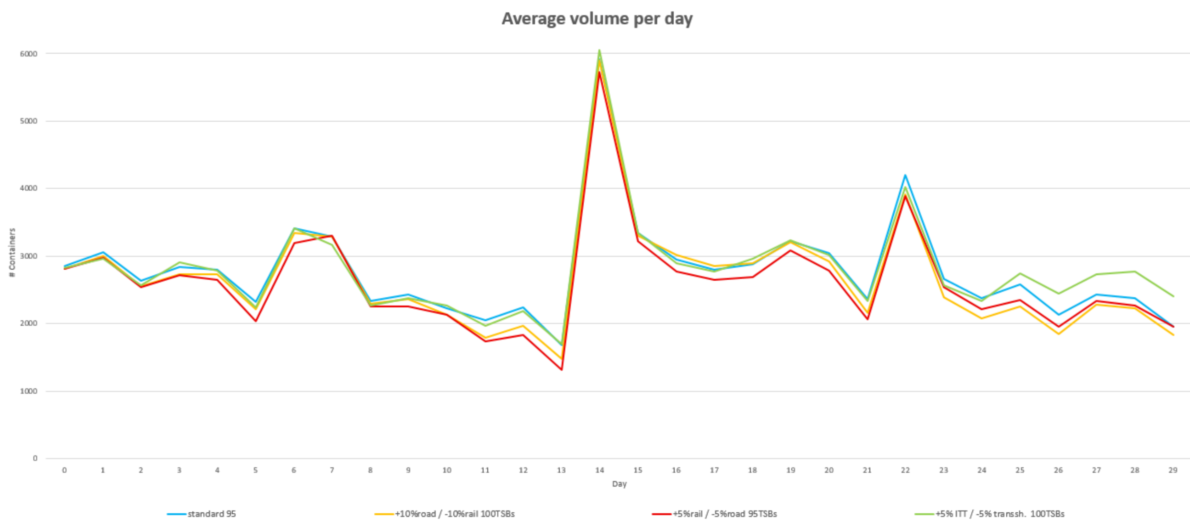

Figure A.31: Design 3 main vehicle settings of modal share scenarios. Daily average hourly total volume to be handled.

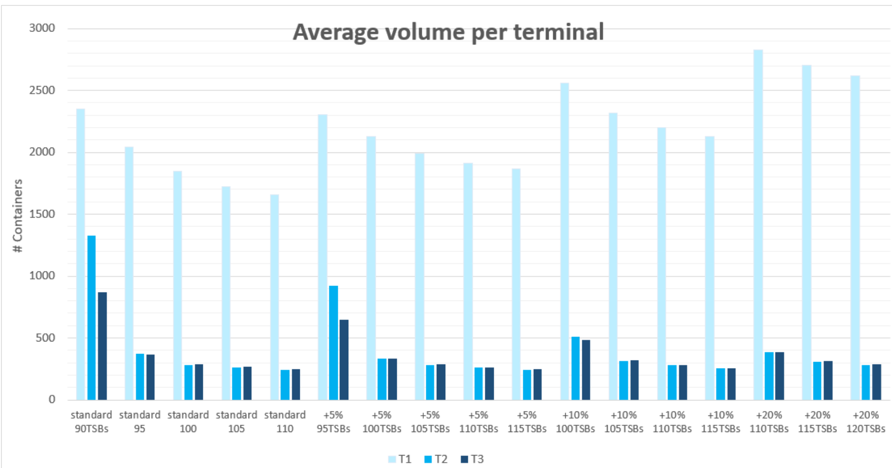

Figure A.32: Design 3 demand scenarios. Average volume to be handled per terminal.

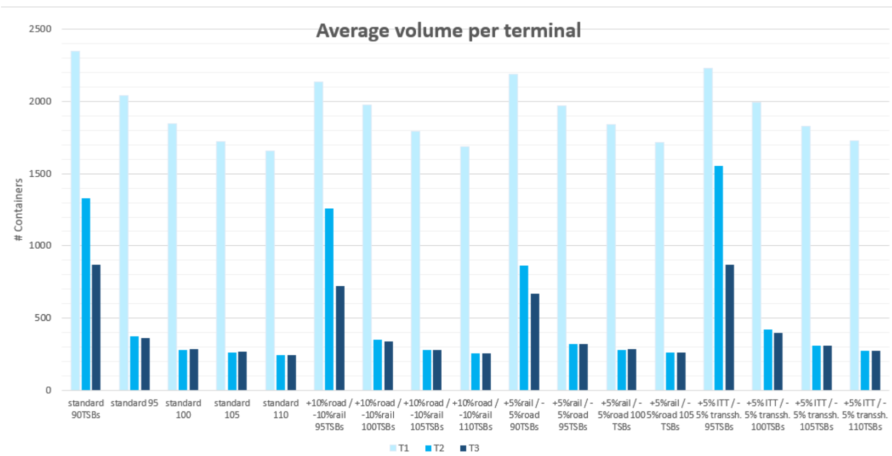

Figure A.33: Design 3 modal share scenarios. Average volume to be handled per terminal.

Volume T1	90	95	100	105	110	115	120
standard	113.8	-9.4	-17.0	-21.5	-19.9		
+5%		54.4	-17.2	-23.2	-15.8	-24.7	
+10%			20.0	-8.3	-13.9	-16.4	
+20%					-8.9	-17.3	-19.1
+5%rail / -5%road	49.6	-10.5	-20.4	-16.9			
+5% ITT / -5% transsh.		110.7	0.6	-15.1	-17.0		
+10%road / -10%rail		73.1	-15.0	-21.1	-17.8		

Figure A.34: Design 3 demand and modal share scenarios slope index. The slope index shows the stability of the demand, and spots if there is a storage buildup.

Volume T1	90	95	100	105	110
standard	41887	39217	37843	36640	35337
+5%rail / -5%road	40035	38030	36726	35260	
+5% ITT / -5% transsh.		40969	38480	37017	36041
+10%road / -10%rail		43104	40510	39071	37939

Figure A.35: Design 3. Distance (in km) covered per TSB over the whole period. The color range ranks the scenarios outputs from best (green) to worse performer (red).

A.1.4. Design 4: Extra switches

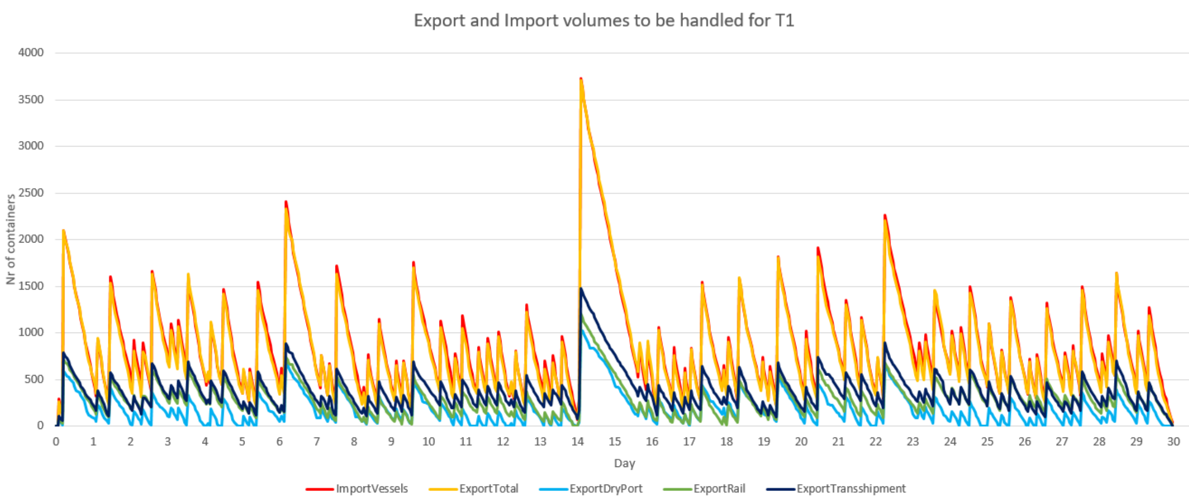

Figure A.36: Import and export volumes to be handled for T1, with the export being divided in its three different storage locations: dry port, transshipment and rail. As the container is handled the volume decreases, therefore low levels are preferred.

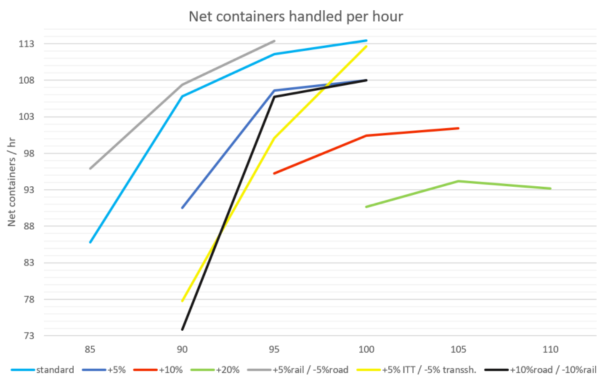

Figure A.37: Design 4. Net containers handled per hour per scenario and number of TSB vehicles used. Net: Total containers/total berth time hours

Volume T1	85	90	95	100	105	110
standard	30.4	30.0	30.0	29.9		
+5%		30.3	30.0	30.0		
+10%			30.1	30.0	30.0	
+20%				30.2	30.2	30.1
+5%rail / -5%road	30.3	30.0	30.0			
+5% ITT / -5% transsh.		30.8	30.1	29.9		
+10%road / -10%rail		30.8	30.0	30.0		

Figure A.38: Design 4 both scenarios data. Schedule end time per scenario. Red cells represents scenarios in which the end time surpassed the maximum expected time (30.6), in which the vessels schedule starts to have a delay, meaning the system setup is not feasible to handle the scenario demand. Unit: Hours.

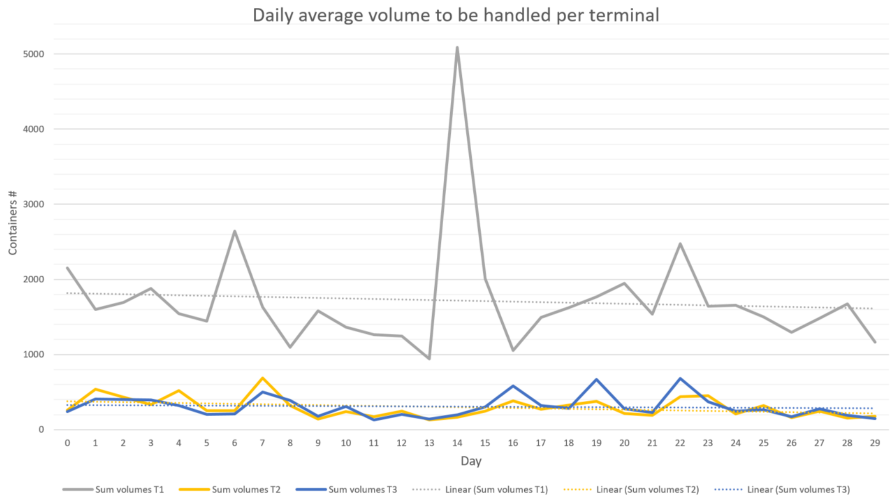

Figure A.39: Design 4. Daily average volume per hour per terminal and their trend-lines in dotted lines

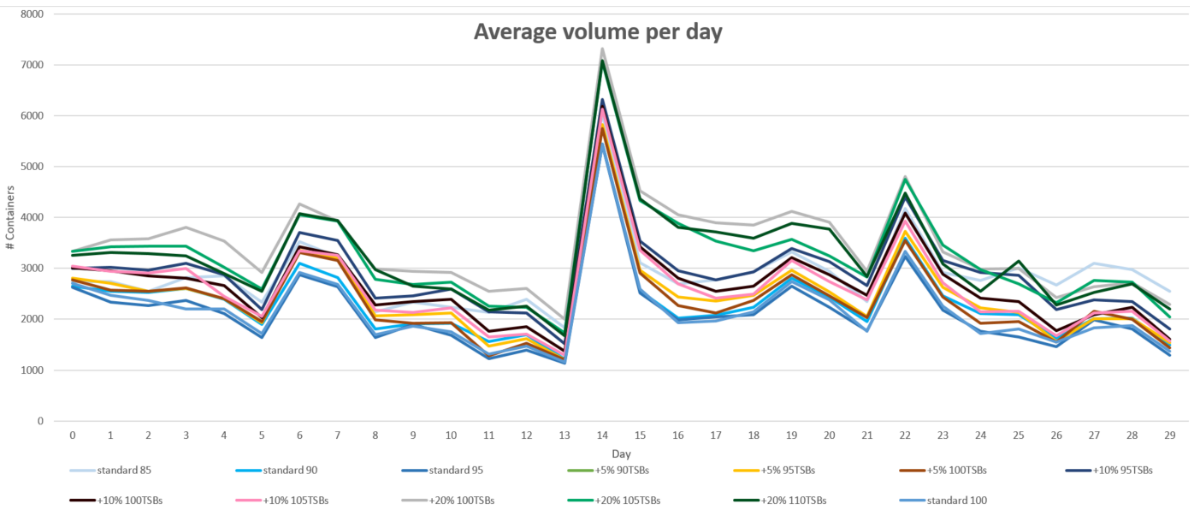

Figure A.40: Design 4 All Demand scenarios. Daily average hourly total volume to be handled.

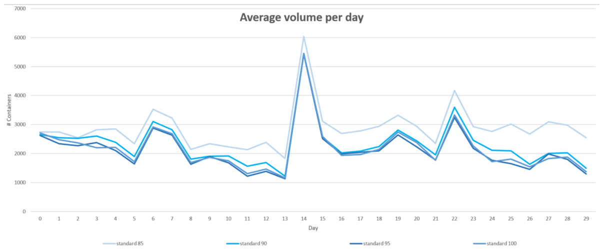

Figure A.41: Daily average hourly total volume to be handled for Design 4, standard demand of T1.

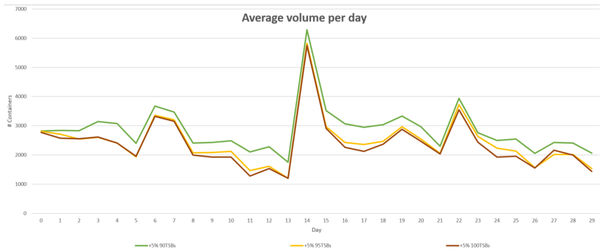

Figure A.42: Daily average hourly total volume to be handled for Design 4, +5% demand of T1.

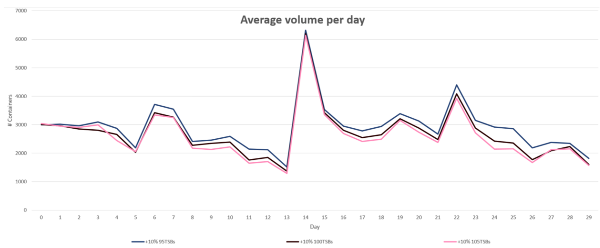

Figure A.43: Daily average hourly total volume to be handled for Design 4, +10% demand of T1.

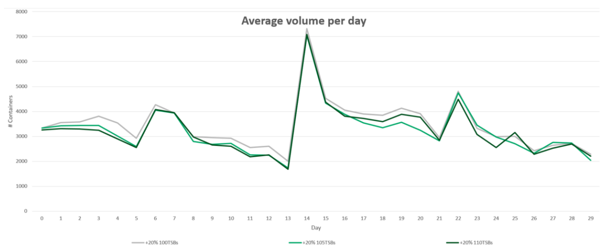

Figure A.44: Daily average hourly total volume to be handled for Design 4, +20% demand of T1.

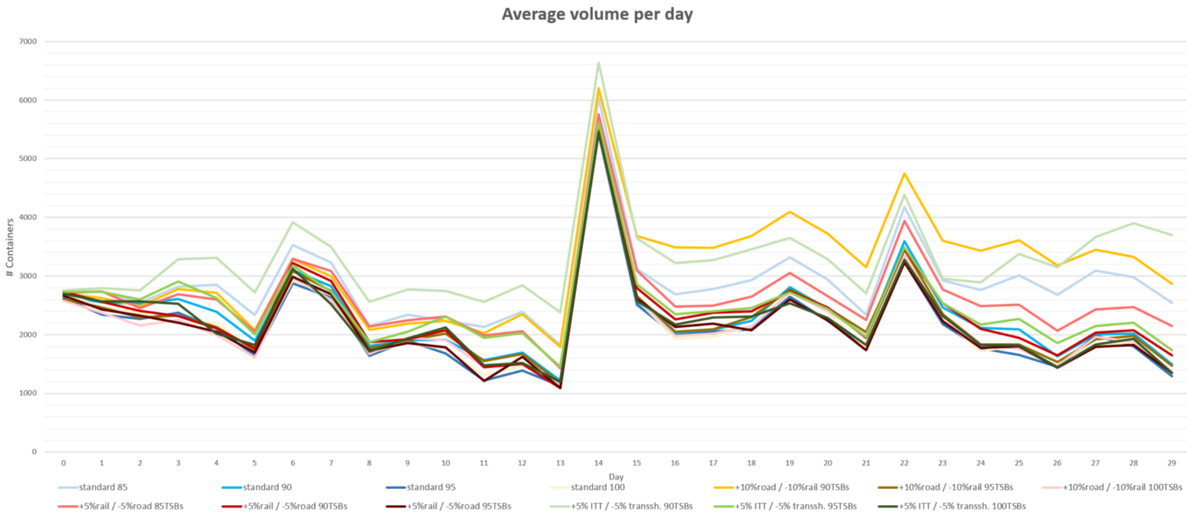

Figure A.45: Design 4 All Modal share scenarios. Daily average hourly total volume to be handled.

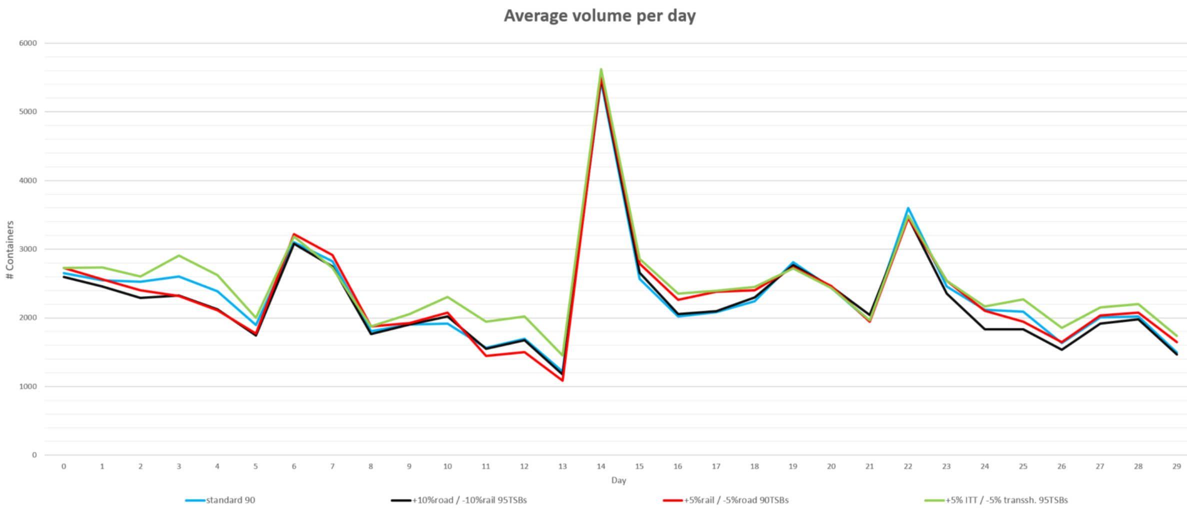

Figure A.46: Design 4 main vehicle settings of modal share scenarios. Daily average hourly total volume to be handled.

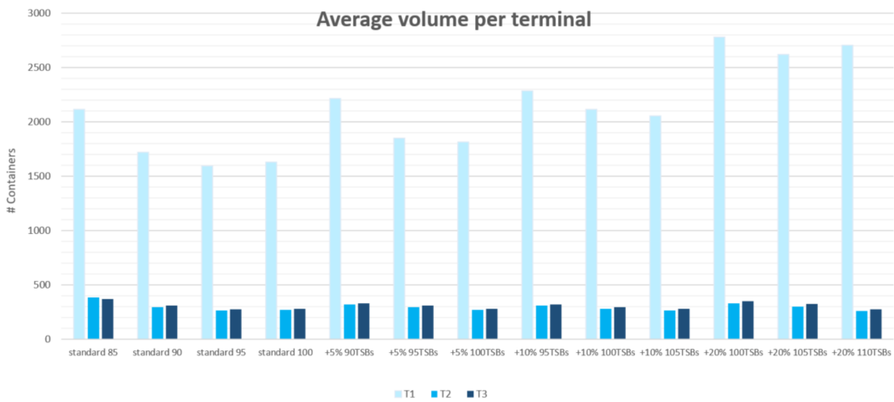

Figure A.47: Design 4 demand scenarios. Average volume to be handled per terminal.

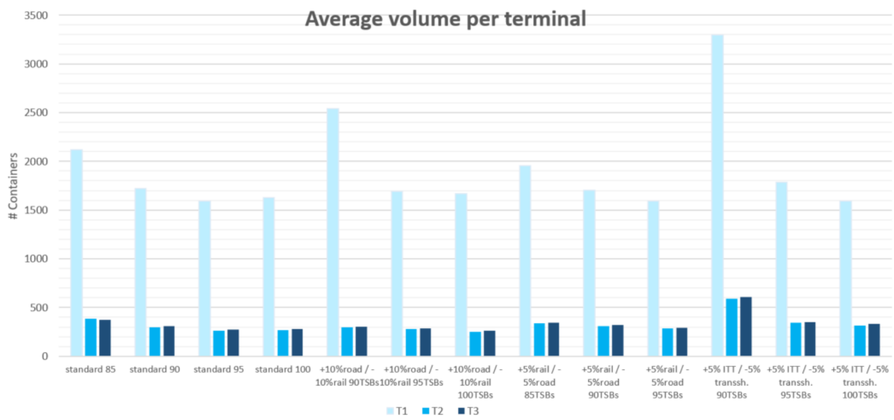

Figure A.48: Design 4 modal share scenarios. Average volume to be handled per terminal.

Volume T1	85	90	95	100	105	110
standard	11.8	-14.0	-15.6	-15.2		
+5%		-14.1	-16.4	-18.1		
+10%			-9.5	-16.0	-20.1	
+20%				-18.1	-14.2	-10.9
+5%rail / -5%road	-1.8	-10.0	-16.3			
+5% ITT / -5% transsh.		22.7	-15.1	-19.4		
+10%road / -10%rail		44.7	-12.4	-11.1		

Figure A.49: Design 4 demand and modal share scenarios slope index. The slope index shows the stability of the demand, and spots if there is a storage buildup.

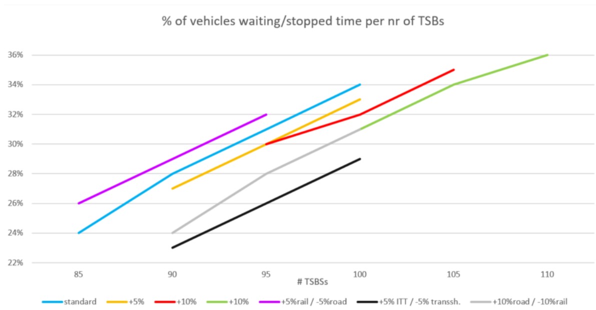

Figure A.50: Design 4. TSBs waiting time % per modal share scenario and number of TSBs.

Volume T1	85	90	95	100
standard	47274	44615	42418	40423
+5%rail / -5%road	45421	42943	40876	
+5% ITT / -5% transsh.		48000	45098	42998
+10%road / -10%rail		49155	45705	43710

Figure A.51: Design 4. Distance (in km) covered per TSB over the whole period. The color range ranks the scenarios outputs from best (green) to worse performer (red).

A.1.5. Design 5: No intra-terminal transportation

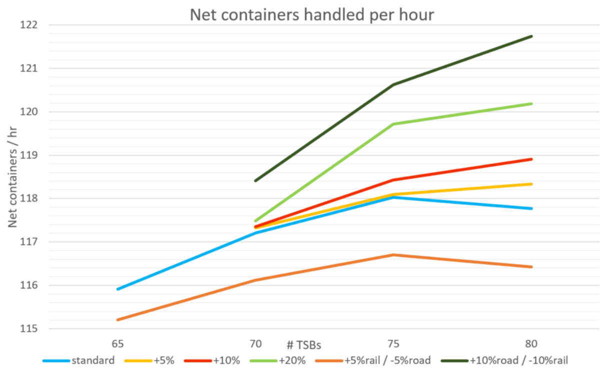

Figure A.52: Design 5. Net containers handled per hour per scenario and number of TSB vehicles used. Net: Total containers/total berth time hours

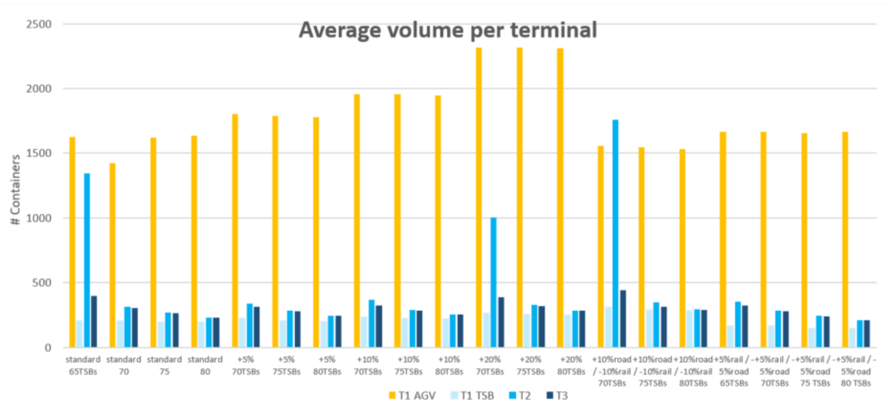

Figure A.53: Design 5 all scenarios. Average volume to be handled per terminal.

Volume T1	65	70	75	80
standard	31.6	30.0	30.0	30.0
+5%		30.0	30.0	30.0
+10%		30.0	30.0	30.0
+20%		31.5	30.1	30.1
+5%rail / -5%road	30.0	30.0	30.0	
+10%road / -10%rail		32.1	29.9	29.9

Figure A.54: Design 5 both scenarios data. Schedule end time per scenario. Red cells represents scenarios in which the end time surpassed the maximum expected time (30.6), in which the vessels schedule starts to have a delay, meaning the system setup is not feasible to handle the scenario demand. Unit: Hours.

Volume T1	65	70	75	80
standard	47.3	-20.8	-19.0	-17.9
+5%		-21.6	-20.0	-19.4
+10%		-21.9	-20.2	-19.0
+20%		18.3	-22.7	-21.2
+5%rail / -5%road	-18.1	-19.7	-19.3	-17.8
+10%road / -10%rail		77.4	-20.5	-17.9

Figure A.55: Design 5 demand and modal share scenarios slope index. The slope index shows the stability of the demand, and spots if there is a storage buildup.

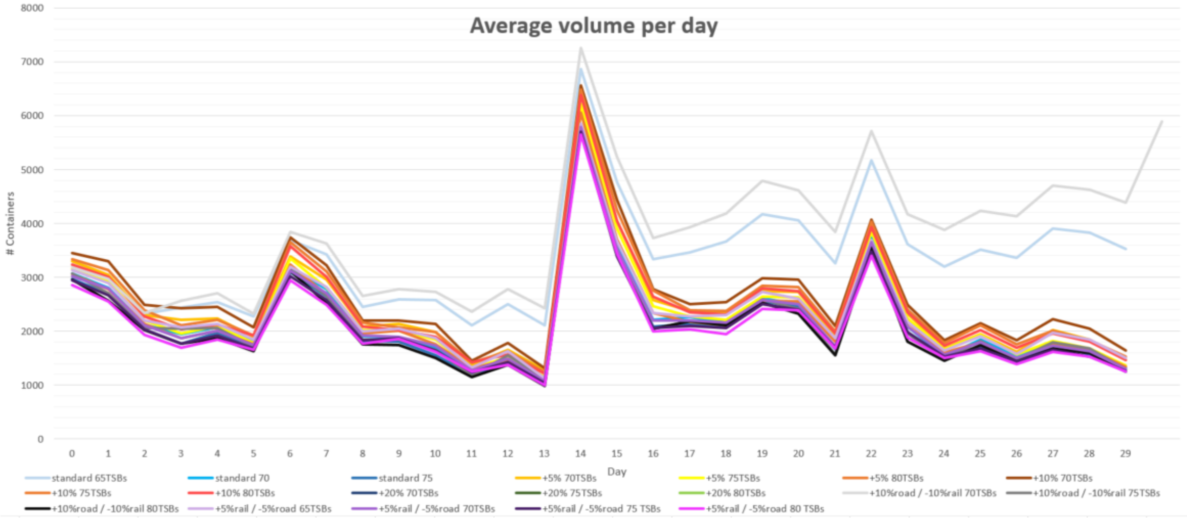

Figure A.56: Design 5 all scenarios daily average hourly total volume to be handled.

Volume T1	65	70	75	80
standard	56084	51399	48480	45816
+5%rail / -5%road	52432	49379	46431	44221
+10%road / -10%rail		57094	52367	49561

Figure A.57: Design 5. Distance (in km) covered per TSB over the whole period. The color range ranks the scenarios outputs from best (green) to worse performer (red).

B

Scientific paper

Design & Simulation of an Integrated Automated Maglev System to Overcome Transportation Challenges between Inland and Seaport Terminals

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Abstract

Port systems face significant challenges such as limited storage capacity, congestion at road access points, and inefficient inter-terminal transportation. Close dry ports, typically 10-40 km from the seaport, offer a solution but lack efficient transport connections. This research investigates the integration of magnetic levitation (maglev) technology, specifically the Transport System Bögl (TSB) Cargo system, to enhance connectivity between a dry port and seaport terminals directly to the berth. Five designs were developed and evaluated using Siemens Tecnomatix Plant Simulation software, focusing on redesigning the dry port and terminal connections. Results indicate improvements in median berth times across all designs, with Design 5 and Design 2 showing the most significant enhancements. Recommendations include continued collaboration with port authorities through simulation case studies, serving as proof of performance for potential integration projects. This study demonstrates the potential of maglev systems to revolutionize port logistics, suggesting further research to refine the model, explore new operational algorithms and terminals coordination methods, supporting continued advancements in port operations technology.

Key words. Maglev, Container transport, Dry port, Port simulation, Inter-terminal transportation

1. INTRODUCTION

1.1. Context and problem statement

In the context of rapidly evolving global trade dynamics, the increase in population, economic activities, and international commerce has significantly boosted the movement of goods, presenting challenges for deep sea container ports globally (Tavasszy and de Jong (2014)). These challenges are compounded by spatial constraints along coastal areas, impacting the development and efficiency of these ports (Cullinane and Wilmsmeier (2011)). The consequent surge in trade operations not only strains port infrastructure but also exacerbates vehicular congestion, leading to environmental pollution and degraded urban quality of life. Moreover, logistical inefficiencies increase operational costs, prolong wait times, and heighten pollution concerns.

To mitigate the adverse effects of escalating container volumes at seaports, the strategic implementation of dry ports, located away from primary port areas, has been proposed. Defined by Roso and Leveque (2002) as inland intermodal terminals directly connected to seaports, dry ports facilitate container pickups and deliveries as if directly at a seaport. These are categorized into distant, midrange, and close dry ports, with this study focusing on the latter—situated at city peripheries with robust road access and infrastructure capacity. Close dry ports primarily enhance container storage space and streamline truck access, reducing city congestion and pollution while offering additional services such as customs clearance and container maintenance (Roso et al. (2009)). Typically, a rail shuttle service transports containers to seaport terminals, however this necessitates intermediate storage.

However, dry ports currently lack a flexible, reliable transport solution for seamless direct connectivity with the berth at main ports, reducing operational efficiency. The intra-port movement of containers introduces further complexities, including high costs, time consumption, and unpredictability, impacting both shipowners and shippers.

Recent advancements in rail systems, particularly the development of fully automated magnetic levitation

(maglev) cargo shuttles, offer a promising solution for these logistical challenges (Siegmund (2021)). Maglev technology uses magnetic fields to levitate and propel trains above tracks, allowing high-speed travel with minimal friction and noise. This technology supports autonomous, demand-responsive container transport with significantly reduced CO2 emissions.
The maglev system's capabilities are well-suited to enhance connectivity between dry ports and seaports, ensuring just-in-time container deliveries directly at vessels' berths. It simplifies inter-terminal transport by eliminating redundant handling steps, providing direct transfers from berths to terminal storage, and reducing operational complexities and costs compared to traditional transport methods like barges or trucks. Additionally, the system can integrate seamlessly with automated guided vehicles (AGVs) in terminals, combining flexibility with existing infrastructures.
Despite its potential, the integration of maglev technology in port logistics remains largely unexplored due to its novelty and the absence of extensive quantitative research. The complexities and technical demands of implementing such a system could necessitate a complete redesign of existing port systems, presenting significant uncertainties about its feasibility and performance. The main concern revolves around the system's capacity to handle the high volumes associated with major ports. This research aims to address these uncertainties, offering insights into the potential integration of maglev technology into port operations and its capacity to manage substantial cargo volumes effectively.

This study is undertaken to fill the gap in quantitative research on maglev technology in port logistics, despite some initial proof-of-concept work by developers. It explores the detailed design, integration, and performance implications of the maglev system, assessing its potential to revolutionize port operations in line with current and future logistical demands.

1.2. Literature review

This literature review explores the diverse methods of container transportation within ports, between terminals, and from ports to inland terminals. It aims to address the primary question: *"What are the various container port transportation methods, and what methodologies are employed to study their integration and effectiveness within different parts of the port logistics?"*

1.2.1. Intra-terminal Transport

Intra-terminal transport research is vital for optimizing the efficiency of moving containers within terminals. It focuses on the machinery and equipment, such as quay cranes and Automated Guided Vehicles (AGVs), which facilitate container movement. Research by Kap et al. (2012) assessed various technologies including AGVs and automated storage and retrieval systems (AR/RS), analyzing their flexibility, cost implications, environmental impacts, and operational resilience. Liu et al. (2002) further explored these technologies, employing quantitative simulations to develop four distinct terminal designs. These studies reveal that integrating multiple container movements into single, efficient operations can enhance terminal performance significantly. Unlike these technologies, the proposed maglev system aims to provide even faster intra-terminal transportation due to its higher speeds, potentially integrating intra-terminal movements with broader logistic networks effectively, which these studies do not address.

1.2.2. Inter-terminal Transport

Inter-terminal transport (ITT) studies, such as those conducted by Duinkerken et al. (2006), have focused on comparing different transportation systems within container terminals, using detailed simulation studies to evaluate the effectiveness of multi-trailer systems (MTS), AGVs, and automated lift vehicles (ALVs). These studies provide valuable insights into how different systems affect terminal efficiency and operational dynamics. Truong et al. (2020) introduced an innovative approach with automated electric rails, designed to meet future demands effectively. These studies highlight the potential of automated, high-capacity transport systems in improving terminal connectivity and efficiency, a concept that aligns with the proposed maglev system which aims to reduce transit times and increase throughput more dramatically than the systems previously studied.

1.2.3. Seaport Terminals to Inland Terminals Transport

The link between seaport terminals and inland terminals has traditionally been dominated by conventional road and rail systems, with innovative solutions increasingly being explored. Hansen (2004) and Gattuso and Cassone (2018) proposed advanced rail solutions such as Automated Guided Wagons (AGW), focusing on reducing handling movements and operational costs. These solutions emphasize the need for efficient, cost-effective transport systems that can handle substantial volumes, similar to the proposed maglev system, which offers the additional benefit of higher speeds and potentially lower environmental impact. Unlike these rail-based solutions, the maglev system proposed in this research could operate at speeds unmatched by traditional systems, suggesting a significant improvement in the efficiency of linking seaport and hinterland terminals.

1.2.4. Integration and Research Gap

While existing studies have contributed significantly to understanding and improving container transportation within and between terminals, they predominantly focus on optimizing existing technologies and layouts. There remains a substantial gap in research related to integrating high-speed maglev technology within port logistics. Most studies have not addressed the potential of maglev systems to operate across different transport scopes—within terminals, between terminals, and to hinterland locations—within a unified system. Moreover, none of these study quantitatively the direct connection of the dry port to the berth, without intermediate transport, for larger scales and volumes, analysing its possible integration and performance.
This research aims to fill these gaps by designing a comprehensive maglev transport network that enhances efficiency and connectivity across all aspects of port operations. By employing advanced simulation techniques, this study will quantitatively assess the feasibility and operational dynamics of the maglev system, exploring its potential to transform traditional port operations significantly. This approach not only addresses the limitations identified in previous studies but also expands the scope of technological integration in port logistics, offering insights into a novel, potentially more efficient method of container transportation.

1.3. Research Objectives

The primary goal of this research is to design a comprehensive network layout and terminal arrangement that supports the operational needs of the maglev transport system. This includes optimizing intra-terminal operations within the seaport, facilitating inter-terminal transportation, and ensuring a seamless connection to the dry port. The initial system design and operational scheduling will be approached intuitively, acknowledging the complexities involved and the constraints of the research timeline. Detailed optimization will be reserved for future studies.
The study will develop a robust simulation model to mirror the operational dynamics of the proposed maglev system. This model will help assess the interactions between the maglev system and handling equipment, evaluate performance metrics, and identify potential bottlenecks and operational issues under various scenarios. The objective is to provide insights that will assist stakeholders in implementing the maglev system effectively, aiming to transform container transportation within ports and enhance trade logistics, environmental sustainability, and overall maritime sector progress.

1.4. Research Scope

The focus of this study is narrowed to designing and modeling a terminal network that connects one seaport terminal with an adjacent dry port terminal. External terminals—including two container and a barge terminal—are integrated into the simulation as black boxes to maintain smooth container flows without explicit modeling of congestion effects. Figure 1 depicts this in a network flows sketch. Operational emphasis will be placed on efficient vessel loading and unloading, as berth times are crucial performance indicators for port stakeholders. Although this research primarily assesses operational feasibility, cost factors will be briefly considered to ensure the practicality of the design.
This research is conducted in collaboration with Max Bögl, the owner of the TSB Cargo maglev transport system, combining academic objectives with business applications. TU Delft focuses on addressing the knowledge gap by integrating inter-terminal, intra-terminal, and dry port transportation into a cohesive system with a direct berth connection, enhancing the practical understanding of maglev technology in port operations.

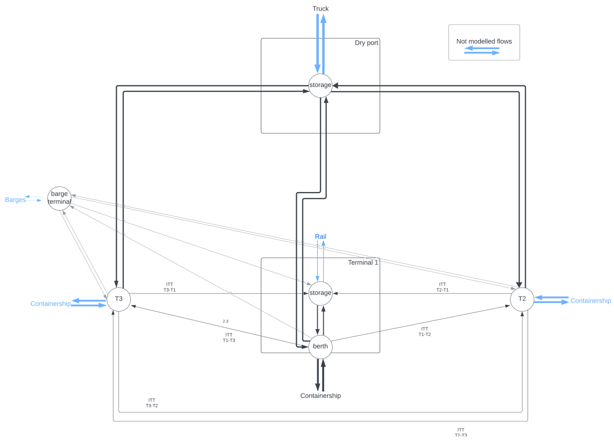

Fig. 1: Network flows sketch. Blue arrows indicate the inflow and outflow out containers in the system that are not being modelled in the simulation study.

1.5. Research Questions

The overarching research question, derived from the stated objectives, is: *"How can a maglev transport system be integrated into seaport logistics, connecting it to a dry port, and what impact would this integration have on port operations?"*
This inquiry will be explored through the following sub-questions:

- Which are the possible system designs & layouts for integrating a maglev transport system into seaport logistics, connecting this one to the dry port ? (Chapter 2)
- What is the performance of the system designs? (Chapter 4)
- What would be the impact of integrating a ma-

glev transport system in port logistics? (Chapters 4 and 5)

2. System design

2.1. TSB Cargo maglev system

The Transport System Bögl (TSB) Cargo, developed by the German company Max Bögl, represents a breakthrough in magnetic levitation technology for containerized freight transport within port logistics. This system, extensively tested on demonstration tracks in Sengenthal, Germany, and Chengdu, China, offers a specialized cargo version engineered for high efficiency and sustainability in port operations.
The TSB Cargo system reaches speeds up to 150 km/h with an acceleration rate of 1.3 m/s^2, enabling rapid container movement while maintaining low energy consumption. Its design allows operation on tracks with steep gradients of up to 10% and tight curves, providing greater flexibility than traditional rail systems. Additionally, the system features minimal noise pollution and low CO2 emissions, aligning with environmental sustainability goals.
Containers travel autonomously, enhancing scheduling flexibility and operational efficiency. The system's integration with existing port infrastructures, such as cranes for efficient loading and unloading, further optimizes container handling.
The maglev employs advanced switching technology, including X-switches, Y-switches, and slide switches, to navigate complex track layouts and support efficient routing and track utilization within ports. This technology ensures smooth transitions and operational flexibility, crucial for maintaining high-speed movements and minimizing transit times.
This compact overview outlines the TSB Cargo system's key characteristics and operational advantages, setting the stage for its potential integration into port logistics.

2.2. Port reference setting

The design aims to create a versatile system applicable to various port layouts using a specific reference structure to guide the foundational design. The TSB maglev system's flexibility ensures minimal impact on performance across different port infrastructures, including variations in berth shape and track configurations. For simplicity, the reference setting includes three container terminals and a barge terminal linearly aligned along a berthline, with each spaced 2 km apart. The barge terminal is located near the river mouth, 2 km from the coastline, and a dry port situated 20 km from each terminal.
The reference terminal is modeled after the HHLA Container Terminal Altenwerder (CTA) in Hamburg. Key data used in the design are derived from this terminal's characteristics, including terminal size, number of berths, and handling equipment (see Table 1).

Table 1: Data for Reference Port Setting. This setting establishes a standard that can be adjusted to meet the conditions of different port environments, ensuring the adaptability of the maglev system to various global ports.

Attribute	Description
Terminal Size	1400 x 600 m
Number of Berths	4
Quay Cranes	15 QCs (4/berth)
TEU-to-Container Conversion	1.6 rate
Average Utilization	80%

2.3. System network type selection

Within the defined port and terminal settings, seven possible maglev system designs were considered to integrate intra-terminal operations within the seaport, inter-terminal transportation, and connections to the dry port, represented in Figure 2. To select the most viable system design, a weighted decision matrix was utilized, factoring in criteria such as capacity, track length, switch operation times, vehicle driving distance, number of switches, and system resilience.

The evaluation process involved soliciting scores from field experts across various departments associated with the TSB maglev system. These scores, ranging from 1 (poor) to 5 (excellent), were aggregated based on the importance of each criterion, heavily weighting factors like capacity and track length due to their impact on system scalability and cost.
The matrix analysis (see Figure 3) revealed that Designs 5, 6, and 7 outperformed others, indicating higher overall efficiency and system capacity. These designs were characterized by:

- Design 5 (Base Design): Featured a total track length of 50.9 km, offering high capacity and efficient track utilization with minimal reliance on switches.
- Design 6 (Shortcut): Included an additional connection between the barge terminal and another terminal, forming a closed loop within the port to avoid unnecessary trips to the dry port.
- Design 7 (Double Track): Integrated a double track throughout the closed loop, enhancing capacity and resilience but at a higher cost due to increased track length.

These designs were selected for further development and detailed simulation to refine their operational effectiveness and cost-efficiency. The preliminary nature of this assessment highlights the need for continued evaluation and refinement throughout the design process.
The following table (3) summarizes the decision matrix outcomes for the designs considered, guiding the selection process for further development.

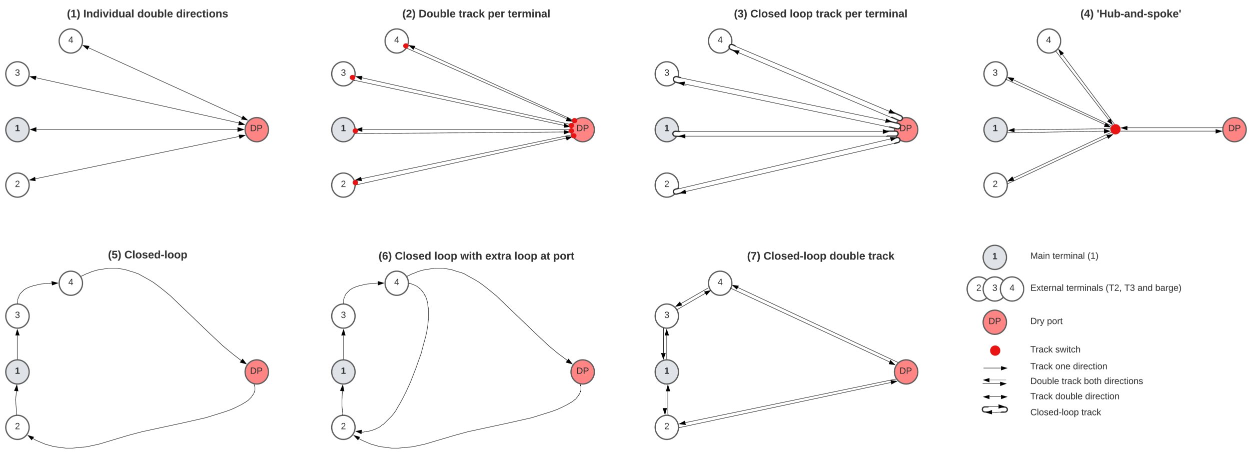

Fig. 2: Different options for maglev network system design and the connections between the four port terminals and the dry port. Source: own design.

Criteria	Weight	Design 1	Design 2	Design 3	Design 4	Design 5	Design 6	Design 7
Capacity	5	1	4	4	3	4	4	5
Track length	4	4	1	1	3	5	4	2
Switches operations time	3	4	1	4	1	5	5	5
Vehicles driving distance	2	5	5	5	5	3	4	3
Nr. of switches	1	4	2	4	2	5	5	4
System resilience	1	2	4	4	3	2	3	5
total		49	43	54	45	68	67	63

Fig. 3: Systems ratings. Score: 1 (poor) to 5(excellent).

This data-driven approach ensures that the maglev system designs selected are optimally aligned with operational needs and cost considerations, setting the stage for detailed design and simulation work in subsequent phases.

2.4. Base design - Design 1

This base design serves as the starting point for all others, with subsequent designs detailing specific adaptations and referring back to this standard. The design of the maglev system focuses on some key aspects: the berth connection, yard storage, and rail connection, as well as the layout of the dry port terminal and its connectivity to the seaport; discussed next. The final sketch of Design 1 is presented in Figure 4.

2.4.1. Berth Connection

The maglev system's berth connection addresses the inefficiencies of current dry ports by eliminating temporary storage needs and ensuring just-in-time delivery of containers directly to the vessels. This direct connection reduces additional handling and costs, enhancing operational efficiency. The design features two parallel tracks along the berth: a primary track linked directly to the quay cranes for immediate loading and unloading, and a secondary 'fast track' for vehicles targetting other terminals. This configuration allows for flexibility in managing traffic and reduces congestion at the berth, particularly beneficial in high-volume ports. Additionally, optional modifications, such as extra switches along the berth, can be made to accommodate varying port demands, illustrated in future design alterations.

2.4.2. Yard Storage

The yard storage design focuses on efficient container management with two main layout options: parallel and perpendicular. The preferred parallel layout aligns the TSB track with the cantilever RMG rails, allowing seamless access to containers on the vehicles. This setup avoids the logistical complexities and space requirements of a perpendicular arrangement, which would necessitate multiple switches and increased track length. The parallel design is thus chosen for its efficiency, reducing switch operations and track usage. Detailed simulations in later stages will refine these storage configurations to optimize space and handling efficiency further.

2.4.3. Rail Connection

Improving rail loading and unloading efficiency is a critical component, particularly with projected increases in rail usage. Traditional operations involve multiple handling steps that introduce delays and inefficiencies. A different considered strategy was to introduce a parallel TSB track specifically for positioning containers directly at rail loading points. However, using lift AGVs in combination with racks proved superior. This method, implemented at APM Terminal in Maasvlakte, Rotterdam (APM (2023)), uses lift AGVs to efficiently move containers to racks for quick and independent crane access, optimizing transport efficiency and minimizing waiting times, as TSBs and AGVs operate concurrently but independently. This setup enhances operational flow and reduces potential congestion by strategically placing containers near rail points.

2.4.4. Dry Port Design

The dry port is structured to facilitate efficient handling and storage of containers, segregated into distinct export and import sections. This design incorporates four parallel TSB tracks, each serving multiple container blocks, with dedicated RMGs for handling truck operations and additional cranes for TSB interactions. The layout supports efficient container transfers between the storage areas and the TSB vehicles, optimizing the flow and minimizing handling times. Trucks access the terminal through designated gates, with separate routes for export and import operations to streamline traffic and enhance safety.

2.4.5. Connection Seaport - Dry Port

The connectivity between the seaport and the dry port is crucial for maintaining the flow of containers. The design utilizes a one-direction closed-loop track system to facilitate efficient transport operations, with potential for expansion or modification based on future needs. This system layout ensures robust connectivity and allows for operational adjustments in response to disruptions or increased demand.

The final design integrates all the aforementioned elements into a cohesive system that addresses the current and future needs of port logistics. This system is designed to be scalable, with the potential for further expansion or reconfiguration to accommodate changing operational requirements. Detailed simulations and continuous evaluations will help refine the design, ensuring it meets the high standards required for modern port operations. This comprehensive design approach ensures that the maglev system is not only capable of meeting current port logistics demands but is also adaptable to future changes and increases in container traffic. The system's flexibility, efficiency, and reduced environmental impact position it as a forward-thinking solution for modern port challenges.

2.5. Extra designs

In addition to the base design outlined previously, several alternative designs offer variations and enhancements to address specific challenges and optimize system performance within the port logistics framework. Each design introduces modifications tailored to different operational scenarios and objectives.

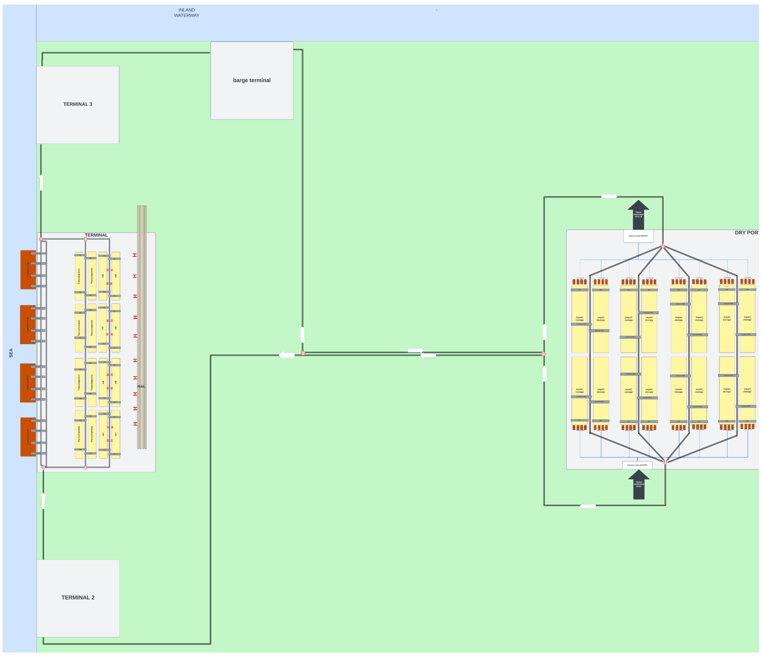

Fig. 4: Full Design 1 sketch. Not in real scale.

2.5.1. Design 2: Shortcut Connection Around the Port

Design 2 introduces a strategic shortcut track spanning approximately 8.9km, connecting the barge terminal directly to terminal 2. This addition aims to streamline inter-terminal transportation, reducing travel distances and enhancing operational efficiency. The shortcut track serves as a crucial pathway for vehicles engaged in inter-terminal transfer operations, facilitating swift transfers between various terminal pairs. Additionally, it enables the efficient utilization of empty vehicles to rectify import-export imbalances across container terminals. By optimizing container flows and resource allocation, Design 2 enhances the overall performance of the port logistics infrastructure.

2.5.2. Design 3: Double Track

Design 3 explores the implementation of double tracks to accommodate two-directional movement within the system. However, complexities arise during the detailed design phase, particularly regarding the handling of import containers at the quay crane, where the destination is unknown until loading onto the TSB. Five alternative designs are formulated, categorized into single-direction and double-direction variants, each with unique infrastructure requirements and operational considerations. After careful evaluation, Design 1.3 (see Figure 5) is selected as the preferred option due to its advantages in enhancing system resilience and operational efficiency.

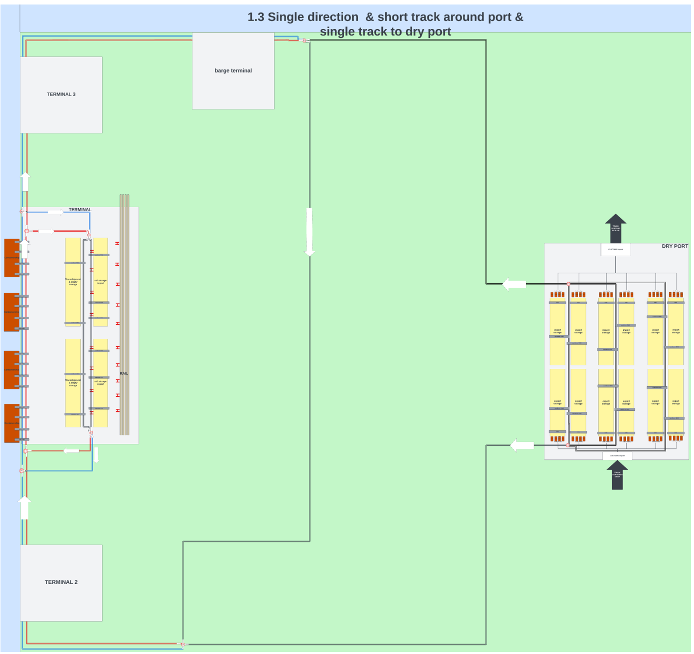

Fig. 5: Single direction & short track around port & single track to dry port. Red circles represent switches and black circles at track intersections represent level changes.

2.5.3. *Design 4: Extra Switches at Berth*

Design 4 enhances the base design by incorporating additional shortcut tracks and switches at the berth to mitigate congestion and improve operational efficiency. The inclusion of three shortcut tracks with extra switches strategically connects the fast track with the primary berth track (see Figure 6), facilitating smoother navigation and bypassing congestion at busy berths. This design modification aims to enhance berth utilization efficiency by allowing concurrent loading operations alongside ongoing activities at adjacent berths.

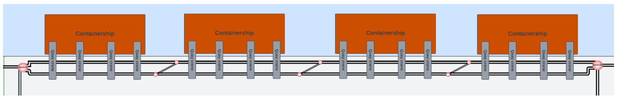

Fig. 6: Tracks design for the extra 'Y' switches, and shortcuts added between the fast track and the berth track. Berth spaces 1 to 4, from left to right.

2.5.4. *Design 5: Standard System without Intra-Terminal Transport*

Design 5 presents an alternative scenario where intra-terminal transportation tasks for rail and transshipment containers are excluded from the TSB system. Instead, Automated Guided Vehicles (AGVs) handle these operations in collaboration with quay cranes. This phased implementation approach allows for gradual testing and scaling up of the TSB system over time, while still accommodating traditional truck-based container handling at the terminal. The challenge with this design lies in coordinating container handling between TSB and AGV systems, requiring adjustments in quay crane operations and storage arrangements. To facilitate the TSB system's connection for ITT container handling, a small storage area equipped with an RMG crane is located adjacent to the berth track, as shown in Figure 7. This setup enables the efficient unloading and storage of containers from other terminals. Initially considered, positioning this storage area next to the fast track was ultimately rejected due to potential exacerbation of export-import volume imbalances, as it would allow TSB vehicles to leave directly after unloading, without handling import containers.

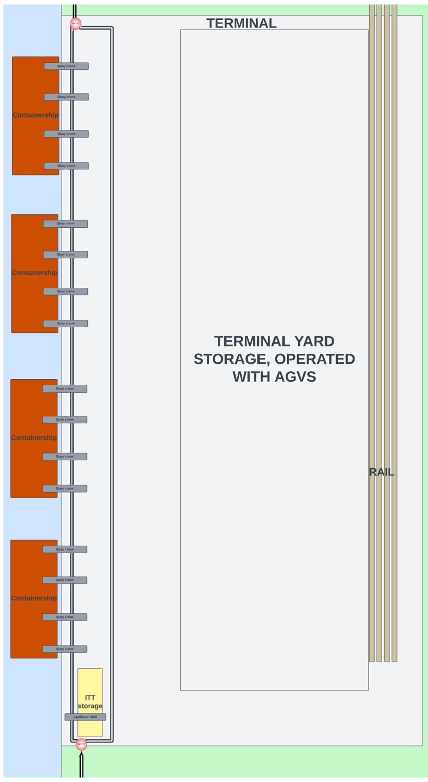

Fig. 7: Terminal layout without intra-terminal transport performed by TSB.

Each design variation offers unique advantages and challenges, contributing to the comprehensive exploration of potential enhancements to the port logistics system. Through rigorous evaluation and simulation studies, the most effective design solutions will be identified and integrated into the overall system architecture.

3. Simulation

Simulation is essential for evaluating port logistics systems, offering a virtual environment to analyze operations, identify bottlenecks, and test scenarios. Using Siemens Tecnomatix Plant Simulation software (version 2201), we developed a simulation model to assess the performance of the five designs introduced earlier. This approach allows stakeholders to evaluate system performance across various conditions, aiding decision-making for efficiency improvement, cost reduction, and overall operational enhancement.

3.1. KPIs

The following KPIs are used to provide a comprehensive framework for evaluating the efficiency, performance, and utilization of the TSB system within the port terminal simulation model:

- Vessels Berth Times
- Utilization of Vehicles
- Utilization of Handling Equipment
- Total System Handled Volumes
- Volumes Stability – slope index
- Real-time Volumes per Terminal

3.2. Assumptions

- Quay Cranes (QCs) lack information on import containers, with container destinations known only upon loading onto the TSB.
- The entire port's container demand volume is handled by the TSB.
- Loading and unloading order of containers is disregarded.
- Import containers are assigned to the four QCs of the berth, while export containers do not have an assigned QC.
- TSB loading operations function on a double cycling loading basis, allowing QCs to unload the TSB and load a new import container.
- The distance between the barge terminal and the dry port (DP) and between DP and Terminal 2 (T2) is assumed to be 20km.
- Priority is given to vessels that arrive earlier, eliminating other type of priority distinctions.
- Road containers are dropped off and picked up by trucks at the dry port.
- Rail containers are stored upon the rail cars' arrival on rail storage blocks by a separate system, lift-AGVs. Same the other way around, upon rail car arrival the lift-AGVs pickup the containers from the rail storage and take them to the railside.
- The lift-AGVs and trucks dont interfere in the RMGs operation with the TSB system.
- Containers arriving by barges are available at the barge terminal for subsequent transportation to the corresponding terminal.
- All containers are available at their corresponding storage once the vessel berths.

3.3. Parameters

- Loading time for QCs (Tang et al. (2020)) :
  - Single cycle: 105 seconds
  - Double cycle: 160 seconds
- Loading time for RMGs (Saanen and Valkengoed (2005)):
  - Single cycle: 90 seconds
  - Double cycle: 140 seconds (assumption)
- Speed of TSB: 150 km/h (Bögl (2021))
- Acceleration of TSB: 1.3 m/s^2 (Bögl (2021))
- Buffer times for external terminals (explained in section 3.5).

3.4. Input data

Terminal's input data for the simulation is based on data from HHLA three Hamburg terminals (HHLA (2022)) and Hamburg port four container terminals container aggregate data on volumes, modal share, transshipments, empty containers and vessel calls (of Hamburg HPA (2023b) , of Hamburg HPA (2023a) & of Hamburg HPA (2023c)).
General Hamburg container terminal aggregate data volumes year 2022:

- Total volume: 8.3M TEUs (6.396M for the 3 HHLA terminals)
- export 49.4%
- import 50.6%
- Transshipment containers: 34.9%
  - on this transshipment share, inter-terminal transport containers are assumed to be 5%
- Share container hinterland traffic per mode
  - road: 47.3%
  - rail: 50.5%
  - barge: 2.2%

Assuming the CTA terminal handles 40% of the total 3 HHLA terminals in Hamburg, this equates to 2.558.400 TEUs annually. Using a conversion factor of 1.6 for passing from TEUs to containers (source: Consulting (2022)), this translates to 133,250 containers per month and 80 monthly vessel calls. The dataset was compiled for a month-long vessel schedule, featuring volumes ranging from 422 to 7096 containers per vessel, with 2 or 3 vessel arrivals per day. Additionally, the vessel arrival and volume schedules for T2 and T3 was created similarly, with a more stable schedule do to the black box modeling of these terminals. Figure 8 presents the three terminals throughput demand per day.

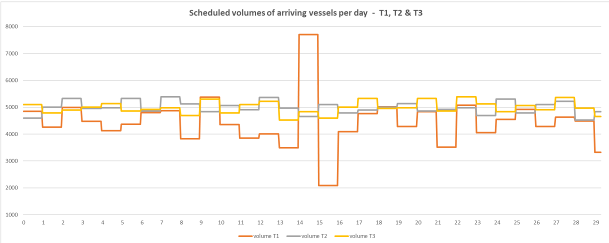

Fig. 8: Scheduled volumes of arriving vessels per day - T1, T2 & T3.

The design was considered a success if the system is able to meet all the container demand on time, without a buildup, and has the objective of beating Germany's vessels' median berth time of 18.96 hours (source: **?**).

3.5. Simulation Modeling

Figure 9 depicts the simulation model events graph for Design 1, encompassing various agent groups, including trucks, rail lift-AGVs, vessels, quay cranes, vehicles (TSBs), container export, and container import. Trucks and rail lift-AGVs agents, highlighted in blue, are not directly integrated into the simulation model due to their low impact on the results, as they aren't closely linked to the TSB system. However, these agents' events are still mapped in the figure for providing a general view of the whole system's processes relationships. Moreover, container import and export groups serve as connectors between agents, however these are passive agents, awaiting loading or unloading without taking independent actions or decisions. TSB vehicles, the primary agents, interact with all other groups, except for AGVs and trucks, as explained.

Vehicles entering the external terminals are given a buffer time to realistically simulate the duration they would typically spend in terminal operations, encompassing all container exchanges between the yard and berth. This buffer time, set at 13.50 minutes, is calculated based on the likelihood of a container being destined for the terminal and the time required to complete a circuit around the terminal, assuming no congestion.

As mentioned, the events graph is made for Design 1. Additional designs 2-4 incorporate slight modifications as described in the previous chapter. Design 5, however, incorporates more differences in the modelling. The key adaptations and assumptions for this design include:

- AGV Implementation: AGVs are deployed only in Terminal 1 (T1), while Terminals 2 (T2) and 3 (T3) continue to rely on TSBs for transport operations.
- Handling of Container Types: TSBs are responsible for managing import Intra-Terminal Transport (ITT) containers and dry port containers, while AGVs handle all transport from the terminal yard to the vessels' berth, including rail and transshipment containers, as well as export ITT containers.
- QC Capacity: The Quay Cranes (QCs) are equipped to handle both AGV and TSB containers, and have the capacity of selecting containers based on their intended mode of transport.
- Availability of AGVs: AGVs are always available at the berth when no TSBs are available, ensuring continuous operation.
- Operation Time: After loading or unloading an AGV, there is a 15-second interval for the next AGV to be positioned and for the next QC operation to commence.
- TSB Container Assignment: Each TSB container is assigned both an origin QC and a destination QC, in contrast to TSBs that do not have defined QC assignments.
- AGV Operation Mode: AGVs operate on a single-cycle basis, performing only one operation at a time, unlike TSBs, which can perform sequential unloading and loading operations.
- System Halt: If there are no containers available for TSB handling, the system will pause, and TSBs will wait upstream of Terminal 2.

3.6. Validation & Verification

The simulation model undergoes a thorough validation and verification process to ensure its accuracy and realism. Validation methods include comparing model outputs with real-world data, incorporating field expert opinions, and conducting sensitivity analyses to test the model's responsiveness to variable inputs. Verification involves rigorous unit testing of individual components, scenario testing across different designs to evaluate performance impacts, and gathering user feedback to confirm the model's operational fidelity. These combined efforts ensure that the simulation reliably mirrors actual terminal operations and effectively represents the dynamics within the transport system.

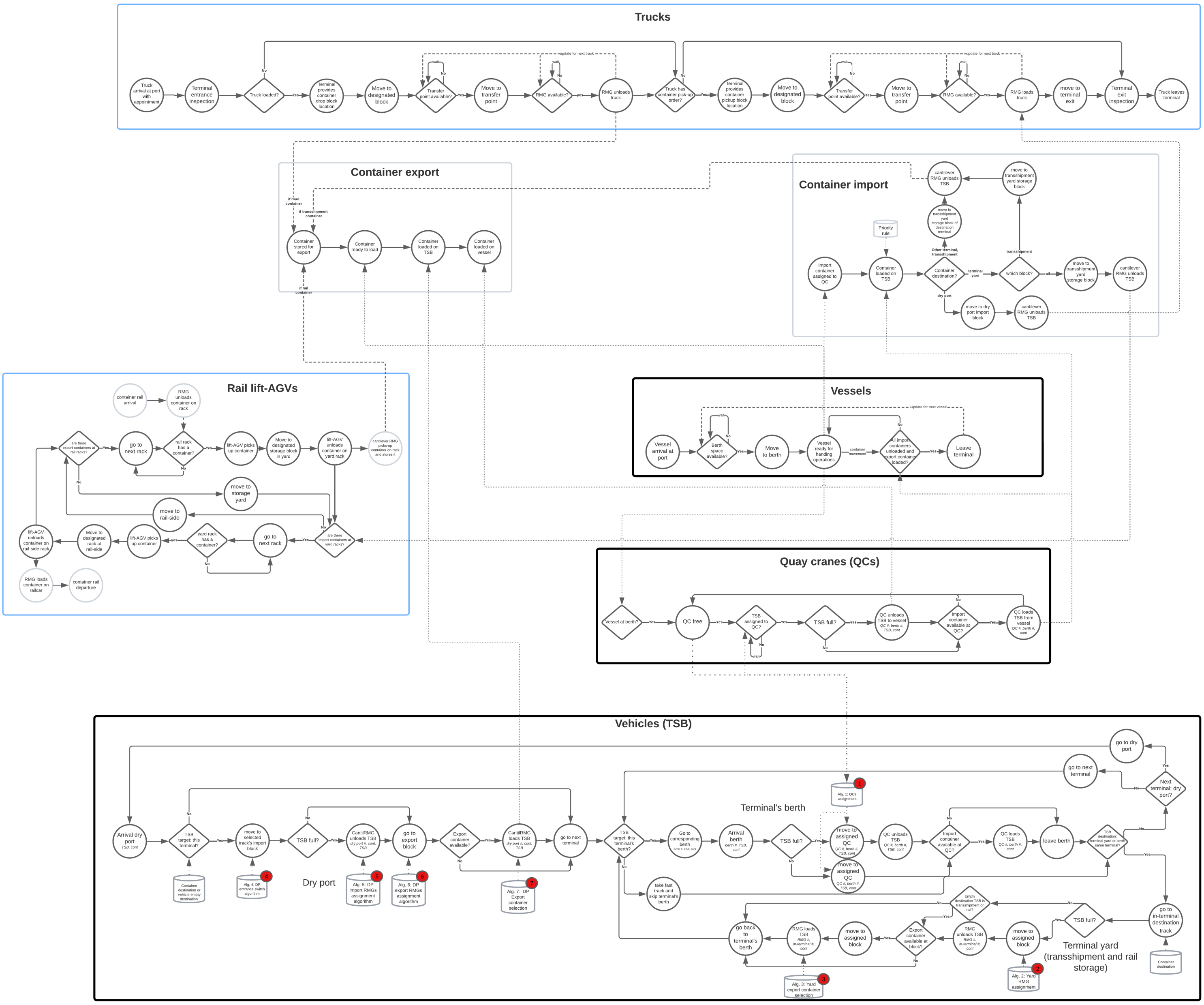

Fig. 9: Events graph. Blue boxes represent the non-modelled agents, grey boxes the passive objects. Red circles indicate the algorithm used, with its assigned number.

4. Scenarios & Results

4.1. Scenarios

Each design undergoes testing across various scenarios, categorized into two groups. The first set comprises four scenarios involving adjustments to the demand volumes of T1: the base scenario, +5% demand, +10% demand, and +20% demand. The second set includes four scenarios focusing on changes in modal shares: the base scenario, +10% road/-10% rail, +5% rail/-5% road, and +5% ITT/-5% interterminal transshipment. Each scenario is evaluated across multiple different operational configurations of TSBs, between 80 and 120, depending on the specific scenario, to analyze the impact on the required number of vehicles and the resulting outcomes. The scenarios with varied demand volumes are designed to assess the system's responsiveness to increases in demand, identify potential bottlenecks, and determine the system's capacity. Furthermore, these scenarios aim to ascertain whether increasing the number of vehicles can effectively manage heightened demand or if a saturation point exists beyond which further improvement is unattainable. The modal split scenarios are intended to explore how different distributions of demand among transportation modes may affect the system's performance. All scenarios will be rigorously tested in this chapter.

4.2. Results

	Design 1	Design 2	Design 3	Design 4	Design 5
Nr of TSB vehicles used	90	90	95	90	70
Average berth time (hrs)	16.3	14.5	18.9	15.7	14.2
Median berth time (hrs)	14.5	12.6	17.0	13.5	11.0
Average containers handled / hr	101.9	115.0	88.2	105.8	117.2
Average net QC moves/hr	25.5	28.7	22.1	26.4	29.3
Average vol. T1 (# cntnrs.)	1687	1608	2044	1719	1628
Average vol External Terminals (T2 & T3) (# cntnrs.)	285	294	370	302	309
Average TSB ditance travelled (km)	44681	41749	39217	44615	51399
Average TSB waiting time %	29%	31%	28%	31%	15% (+ 2% stopped)

Fig. 10: Summary comparison of main performance indicators for all designs main settings. For each indicator, the color range ranks the designs from best (green) to worse performer (red).

Examining Figures 11 and 12, Design 5 demonstrates the best performance in terms of median berth times, while Design 2 surpasses all others in terms of containers per hour handled. The positive performance of Design 5 is attributed to the combined use of AGVs and TSBs, albeit with certain relaxation assumptions, which will be elaborated upon in the Discussion next. Notably, Design 5, similar to Design 2, incorporates a shortcut track around the terminal, offering dual benefits. This shortcut track, apart from benefiting the system by decreasing vehicles travelled distances for ITT transportation, it also helped out balancing the load over the terminals, making the system more efficient. Additionally, the remaining designs follow the performance order from best to worst as follows: Shortcut design, extra switches, standard, and double track designs. The red line in the Figure denotes the reference benchmark of median berth time in Germany, 18.96 hours (source: UNCTAD (2019)), which all TSB settings for Designs 2, 4, and 5 outperform. However, Design 1 would require at least 90 vehicles, and Design 3, 95, to meet this benchmark.

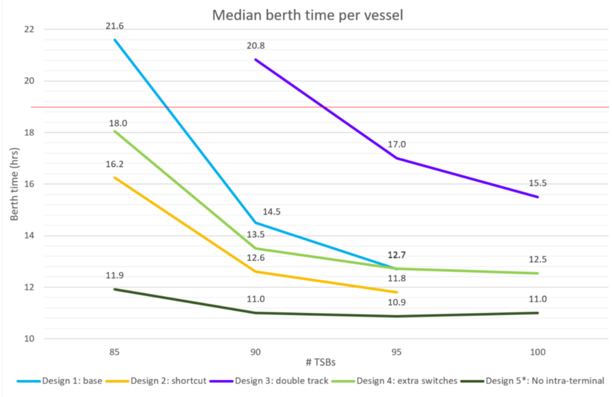

Fig. 11: Median vessels berth times graph for all Designs base scenarios and number of TSB vehicles used. The red line marks the reference benchmark of median berth time in Germany: 18.96h. Note that the X axis for Design 5 is different, and corresponds to: 65, 70, 75 and 80 . Unit: Hours.

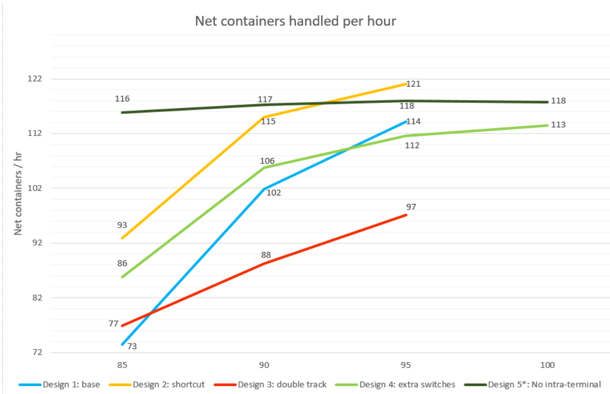

Fig. 12: Net containers handled per hour per Design base scenario and number of TSB vehicles used. Note that the X axis for Design 5 is different, and corresponds to: 65, 70, 75 and 80. Net: Total containers/total berth time hours.

Furthermore, Design 4 outperforms the standard design for smaller numbers of vehicles, especially for vessels at berth space 3 and 4. However, the base design outpaces Design 4 for 95 or more vehicles, as excessive vehicles at the berth render the extra switches counterproductive.
Figure 13 show similar performance for all designs but Design 3, performing notably worse. This design exhibits the poorest performance due to simultaneous loading on both berth tracks, resulting in a lack of a dedicated fast track. Consequently, vehicles destined for other terminals also experience congestion, exacerbating system inefficiency.

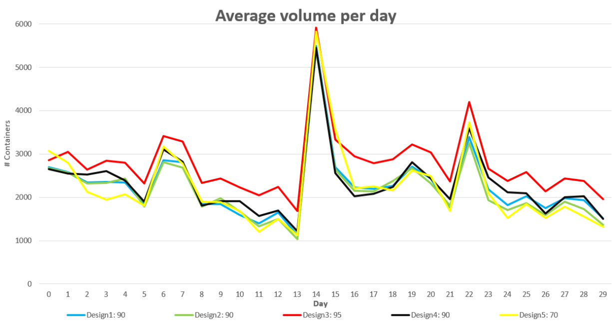

Fig. 13: All designs main vehicle settings. Daily average hourly total volume to be handled. The peaks and fluctuations on volumes correspond to the fluctuation on the vessel schedules' throughputs, which can be compared to Figure 8.

Examining the usage of TSB vehicles in Figure 14, Design 5 emerges as the best-performing once again. This is attributed to its lower presence at Terminal 1, where the majority of waiting time/congestion arises, as external terminals are modeled as black boxes and do not contribute to waiting times. Generally, there exists a direct relationship between waiting times and berth time efficiency in the designs. However, the relation between Design 1 and Design 4 shows a slight deviation: when Design 4 performs better in berth times than Design 1, it also fares better in waiting times, and vice versa.

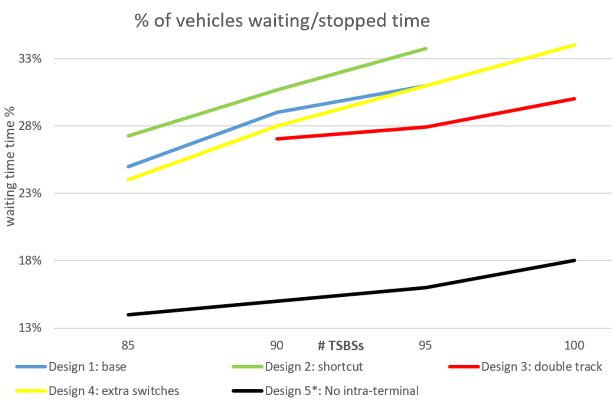

Fig. 14: All designs main scenarios comparison. TSBs waiting time % per design and number of TSBs.Note that the X axis for Design 5 is different, and corresponds to: 65, 70, 75 and 80.

Regarding the distance covered, as illustrated in Figure 5.84, similarity is observed between Design 1 and Design 4, with Design 2 outperforming both. The distance traveled per TSB is naturally higher for Design 5 and lower for Design 3, corresponding to the lowest and highest number of vehicles in use, respectively.

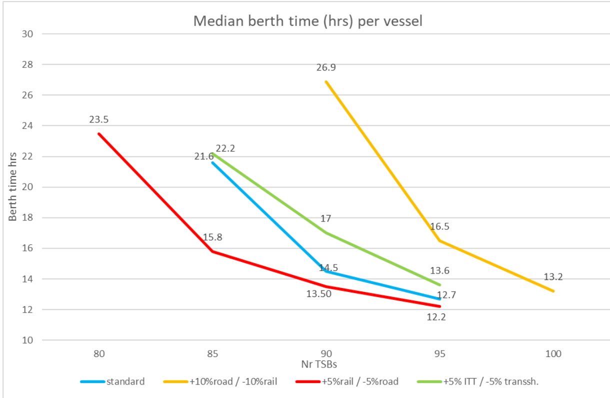

Fig. 15: Design 1 median vessels berth times graph per modal share scenario and number of TSB vehicles used. Unit: Hours.

In summary, all designs, with the appropriate number of vehicles, have demonstrated an improvement in the berth time benchmark, which was prioritized due to its critical importance for terminal operators and the port overall. This has been proven for each design even with demand increases of up to 10% and with each of the tested modal share scenarios. For the +20% scenario, multiple designs achieved median berth times of around 20 hours, only slightly above the benchmark. Despite some system inefficiencies such as congestion, quay cranes have been shown to be the bottleneck in this design. Therefore, increasing the number of quay cranes per berth could enhance system performance, enabling it to handle increased demand volumes while meeting the benchmark goal.

Regarding the different modal share scenarios, in all designs, a consistent trend emerges: the system demonstrates greater efficiency in handling rail containers compared to road containers, which is very obvious do to the big difference in time it takes to go to the dry port compared to the terminal yard. It also shows how ITT containers are handled slightly worse than transshipment ones for the same reason, as they need to travel longer, some of them even more when they have to pass through the dry port for reaching the destination terminal. These trends can be seen for Design 1 in Figure 15.

Furthermore, the productivity of quay cranes in terms of container moves per hour, averaging above 25 moves/hr for most scenarios, falls within industry standards of 25-30 moves per hour (Navis, 2015). Additionally, the objective of balanced volume distribution across all terminals has been achieved, with stable volumes allocated to each terminal.

5. Discussion

5.1. Designs performances reflection

The findings from the conclusion of the results chapter highlight Design 5 as demonstrating the most favorable performance with respect to median berth times. This is primarily attributed to the integrated utilization of AGVs and TSBs, albeit under certain relaxation assumptions. Firstly, it is assumed that quay cranes have the capability to discern, prior to container retrieval from the vessel, the destination of each container, thereby facilitating the selection of either a TSB or AGV container, a feature not yet present in existing systems, posing significant implementation challenges. This design also assumes AGVs are always available at the berth, a scenario that might not hold during peak operational times, potentially leading to delays and congestion.

Design 4 introduces extra tracks at the berth to connect the fast and berth tracks, showing performance improvements over the base design. A combination of elements from Designs 2 and 4 could potentially offer greater benefits by enhancing flexibility and reducing travel distances further. It's worth noting that Design 4 may incur higher costs due to the added switches and short tracks, while Design 2 may also have increased costs owing to the additional 8.9km track compared to Design 1. In contrast to the other designs that exhibit improvements, Design 4 performs worse than Design 1 due to added congestion for external vehicles resulting from the removal of the fast track. To address this issue, an alternative design involving the addition of a third track acting as a fast track could be explored.

Increased demand impacts all designs, leading to higher berth times, especially when demand at Terminal 1 increases by up to 20%. Addressing quay crane bottlenecks by increasing the number of cranes per berth or adapting crane allocation based on berth occupancy and vessel size could help manage these higher volumes more effectively.

The design scenarios revealed trade-offs between the number of TSB vehicles and performance, with increased waiting times and lower utilization rates. Despite performance improvements, each design reached maximum capacity due to bottlenecks at the quay cranes, slowing down the system. Additional trade-offs include the dry port location set at 20km, where longer distances necessitate more vehicles but with less than proportional increase given high terminal movement. Moreover, longer distances mean higher transit time proportions over waiting. Berth space 1 demonstrated higher performance due to lower congestion near the terminal entrance. All in all, as discussed in the results chapter, all of the Designs, with the appropriate TSB vehicle settings, successfully meet the objectives of the system by handling the entire port container volumes and outperforming the berth time benchmark for Germany, which stands at 18.96 hours (source: ?).

5.2. Research limitations

The research introduces a novel integration of magnetic levitation (maglev) transport systems into port logistics, acknowledging limitations due to its preliminary nature and innovative scope.
Firstly, the model simplifies operational complexities such as the allocation of containers to quay cranes. The study does not fully optimize the synchronization of container movements between the yard, dry port, and cranes, which ideally would incorporate advanced strategies like double cycling. Future research should refine this aspect, ensuring a comprehensive system optimization to enhance efficiency.

Another limitation is the modeling of external terminals as black boxes, omitting potential congestion scenarios and assuming perfect operations. A more detailed modeling of these terminals might reveal congestion that could necessitate an increased number of TSB vehicles and more strategic resource allocation to manage volume efficiently. By increasing the number of vehicles and redistributing congestion across the terminals, the overall performance could be maintained without encountering bottlenecks in the early TSB setting, as congestion would be spread across all three terminals rather than concentrated at Terminal 1.

The study also does not model specific operations at Terminals 2 (T2) and 3 (T3), which affects the balance and prioritization of operations across all terminals. Currently, the strategy prioritizes Terminal 1 (T1), focusing on minimizing berth times there while keeping volumes at T2 and T3 low. T2 and T3 operate without specific berth time KPIs, receiving any remaining volume after T1's needs are met. While in this research T2 and T3 are being served successfully, when modelling them, their berth times will also need to be minimized, finding a possible confrontation between the three terminal priorities. The implications of this will be treated next.

Furthermore, optimizing the distribution of containers from the dry port to match the arrival schedules at quay cranes can significantly reduce congestion. Improving container assignment and coordination, especially in how they are allocated to specific cranes, can enhance the overall efficiency of port operations.

5.3. Impact of maglev on port logistics

During the research, discussions were held with experts from the TSB department and representatives from the Hamburg Port Authority (HPA) and Portwise port consultancy. In this meetings the research was discussed, with special focus on the simulation model and the assumptions, as part of the model validation. In addition to that, a key challenge identified was the direct connection of the TSB system to the berth, which diverges from conventional port operations where berth transport is typically facilitated by AGVs or yard trucks. Current methods using railways require intermediate storage of containers, which, while cost-efficient, lack the flexibility and reliability of the TSB system. The TSB's ability to transport containers directly to the berth without the need for consolidation offers a promising alternative, potentially increasing efficiency and reducing congestion.

The comparison between using trucks and the maglev for the connection between the dry port and seaport terminals showed that trucks would not be a viable alternative within the proposed setting. The significant number of trips required for trucks would pose high logistical challenges and incur unnecessary costs. The unpredictability in travel times, potential for congestion, and increased risk of human error further complicate the use of trucks for just-in-time transportation to and from the berth, making a direct berth connection using trucks seem unattainable without intermediate storage.

The implementation of the maglev system (TSB) could transform port logistics by creating a more interconnected and efficient system. This could increase the overall capacity of the port by extending its operations to include the dry port. The port authority could benefit from enhanced inter-terminal transport, reducing congestion around the port and promoting sustainability. Terminal operators would gain from increased storage capacities and reduced internal container moves, potentially offering shorter berth times to vessel carriers.

However, as previously discussed, integrating this system involves coordinating multiple terminals, each with its interests. A potential solution could be a centralized model predictive control (MPC) approach,, where terminals collaborate by sharing schedules and real-time data to optimize operations across all terminals.

Implementing the TSB system would require several stages due to its scale and complexity. Initially, the system could be used solely for inter-terminal transportation, later expanding to include a connection to the dry port. This gradual integration would allow the port to transition road storage to the dry port while maintaining some at the seaport terminals using AGVs. Ultimately, the system could be expanded to include intra-terminal transportation within the yard, necessitating significant restructuring to accommodate the new logistics setup. The scalability of the system could be enhanced by adding parallel tracks at the dry port and increasing the number of TSB vehicles. The flexibility in demand volumes, routing, and scheduling provided by the maglev system would enable dynamic adjustments to operational requirements.

While costs were not the primary focus of this research, they were considered in terms of track length, number of vehicles, cranes, and switches. Funding for such large-scale projects typically involves both public and private investment, and various costing models could be explored to finance the system sustainably.

6. Conclusions, Recommendations & Future Research

In conclusion, this research aimed to explore the integration of the Transport System Bögl (TSB) maglev technology into seaport logistics, particularly examining its potential to revolutionize port operations by establishing a seamless connection between a dry port and seaport terminals. The study focused on the feasibility and impact of this integration on port operations, assessing five distinct design scenarios through simulation modeling.

The findings indicate that integrating the TSB system into port logistics offers a viable solution to traditional challenges such as storage capacity constraints and access congestion, while reducing vessel berth times. By providing a direct connection to the berth from the dry port, the TSB system has the potential to streamline operations, increase efficiency, and reduce environmental impact, opening up a new paradigm for port logistics.

Based on the findings, it is recommended to Max Bögl to continue collaborating closely with port authorities to conduct tailored simulation studies based on specific port requirements and data. This would help validate the TSB's performance for potential integration projects. Additionally, a comprehensive cost analysis should be conducted to fully understand the financial implications of system implementation. Exploring opportunities with smaller, capacity-constrained ports, particularly those in urban areas or those facing expansion limits, could prove beneficial. Initiation of small-scale pilot projects in ports, starting with lower volume links like ITT, is recommended; with a long-term goal of TSB utilization for connecting the port and dry port, which is where the system can really exploit its characteristics, and where it can be disruptive for the industry. Further research is needed on robust information systems, optimization algorithms, financing models, and pricing strategies, including methods to incorporate stakeholders' priorities and demands, thus facilitating collaboration and data sharing among terminals.

Further research should continue refining the model, particularly focusing on optimizing the direct connection to the berth from the dry port and expanding the system to accommodate all terminals. This includes developing new algorithms to balance terminal volumes and exploring optimization models that enhance system efficiency, potentially through centralized model predictive control approaches (MPC). Additionally, further exploration of different pricing models that consider volume and priority could provide insights into the economic aspects of maglev system implementation. Moreover, other possible design different than the ones treated in this study could also be explored.

In conclusion, the integration of maglev technology into port logistics represents a promising opportunity to transform traditional port operations and meet the evolving demands of global trade. By embracing innovation and collaboration, stakeholders can harness the full potential of maglev systems to create more efficient, sustainable, and resilient port environments.

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